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This document contains a System Design Trade Study on the optimum navigation systems for airborne, ground-vehicle and man-portable Unexploded Ordnance detection platforms. This study will be used by Unexploded Ordnance Advanced Technology Demonstration decision-makers to make informed technical and programmatic decisions concerning the use of new navigation and location technologies in the detection, identification and remediation of Unexploded Ordnance.

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March 1995

Prepared by PRC Inc.

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SYSTEM/DESIGN TRADE STUDY REPORT FOR THE NAVIGATION OF THE AIRBORNE, GROUND VEHICULAR AND MAN-PORTABLE PLATFORMS IN SUPPORT OF THE BURIED ORDNANCE DETECTION, IDENTIFICATION AND REMEDIATION TECHNOLOGY

MARCH 1995

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1.0 INTRODUCTION

1.1 Background

The United States Government is in the process of turning many defense sites back to the public for real estate development or to local governments for non-defense uses. Many of these sites are contaminated with large quantities of buried Unexploded Ordnance (UXO). The sensor technologies available on the market today for detection, mapping and remediation of hazardous materials have not been developed to the level that could be directly adapted to UXO. For instance, the Ground Penetrating Radar (GPR) needs further development for automatic adaptation to diverse soil types and various levels of energy attenuation in the ground. The difficulties are pervasive because some of the land areas have been contaminated over many decades of activity and because the nature of the land areas at distinct sites is widely diverse.

The government has instituted an Unexploded Ordnance Advanced Technology Development Program (UXO-ATD) to manage the return of Formerly Used Defense Sites (FUDS) to the public. The Naval Explosive Ordnance Disposal Technology Division (NEODTD) has been designated the technical lead organization of this program. NEODTD will be responsible for the development of reliable systems that can provide economical means of characterizing and remediating sites contaminated with UXO. This program extends from UXO detection systems, through artificial intelligence and data fusion tools, to autonomous excavation and remediation systems.

1.2 Requirement

An essential element of the detection of buried UXO is the accurate location of the ordnance so that, apart from pin-pointing potential dangers, minimal excavation is required to remove the UXO. The Government, therefore, tasked PRC with conducting a System Design Trade Study on the optimum navigation systems for airborne, ground-vehicle and man-portable UXO detection platforms. This study would be used by UXO-ATD decision-makers to make informed technical and programmatic decisions concerning the use of new navigation and location technologies in the detection, identification and remediation of UXO.

The initial navigational goals for accuracy were for 10 meters (95 percent occurrence) for the airborne systems and 0.3 meters for man-portable and ground platform systems. However, as

the study progressed, it became clear that the need for navigational accuracy was driven by the requirements of the GPR sensors. The accurate positioning information required is at the ~.05m level and is essential for proper and effective focusing of GPR imaging.

The Global Positioning System (GPS) algorithms required to provide this high accuracy (0.01m-0.02m) positioning are the same for ground-vehicle, man-portable, and airborne environments. Although these algorithms are very robust, their effectiveness and success depend on the accuracy of the GPS observations. Of these three environments, the airborne platform environment is the most hostile environment for the GPS system due to electromagnetic interference, high accelerations and turbulence. This report therefore focuses on the airborne platform in order to satisfactorily cover all three platforms.

1.3 Discussion

The NEODTD tasked PRC Inc. to assist in developing the subsurface ordnance characterization system using a GPR and other sensors, together with advanced navigation techniques capable of providing very accurate positioning information. NEODTD also directed that the Center for Mapping at Ohio State University should assist PRC Inc. in developing advanced navigation techniques using the Differential Global Positioning System (DGPS).

The approaches offering a high probability of success in identification of UXO exploit data acquisition from multisensor platforms that are sufficiently flexible to adapt to the diverse soil properties prevalent at the contaminated sites. Data acquisition speeds of the different sensors need improvements for covering the hundreds or thousands of acres of contaminated sites over the entire United States. All these technologies, with the GPR being the most stringent, depend on high-rate, high-accuracy positioning data. For instance, the GPR needs positioning information at the 0.05m level with rates of ~50 Hz for proper focusing of GPR imaging and proper calibration of the radar operational parameters. Although the use of differential GPS has made it possible to obtain high-accuracy positioning, robust high-accuracy, high-rate positioning solutions are not available on the market today.

In order to achieve very high orders of accuracy from the GPS, several satellites have to be acquired simultaneously. However, since ground vehicle or man-portable systems have a reduced field of view due to horizon, landscape, buildings, or trees, this accuracy may not be attainable on a continuous basis. Such continuous accuracy is also difficult to achieve with

aircraft or helicopters where maneuvers may shadow the GPS antenna from some satellites. Thus, a method of maintaining high location accuracy as satellites drop in and out is required. This could be achieved through the use of an inertial navigation system (INS). Integration of high-accuracy GPS with inertial navigation has the potential of providing high-accuracy, high-rate robust positioning for effective and proper focusing of the GPR.

The airborne GPR system operates in the frequency domain (step-chirped), which makes it possible to transmit high power over a specified range of frequencies. With high-power transmissions the signal-to-noise ratio (S/N) of the returned signals is adequate to differentiate from the background radiation. Therefore, if the GPS high-accuracy positioning algorithms are capable of providing high-accuracy (0.01m-0.02m) positioning in this high-power transmission environment, then these algorithms will perform equally well or better for the ground-vehicle or man-portable environments where the GPR transmissions are of much lower power. Furthermore, the high dynamics of the airborne environment represent the worst-case scenario for an INS. For this reason, the results of the experiments included in this report are consistently based on data collected in airborne environments. These results represent the worst-case scenario for the GPS/INS positioning of ground-vehicle, man-portable and airborne platforms.

During the reporting period between March 1, 1994 and September 20, 1994, the Center for Mapping conducted a series of concept and design studies using the GPS combined with INS for the navigation of the multisensor platforms, for the calibration of sensor parameters in quasi real-time, and for indexing sensor data position information for post-processing. The results of these studies are incorporated in this system design trade study report on the optimum navigation systems in support of buried ordnance detection, identification and remediation technology development.

Most navigation considerations are common to the airborne, ground-vehicle and man-portable platforms. For this reason the major part of this report contains a description of the GPS/INS navigation, and a performance analysis of the GPS/INS state-of-the-art technology available on the market today. Based on the results of this analysis, the different platform environments and the parameters considered, recommendations are provided for the navigation of each of the platforms (airborne, ground-vehicle, and man-portable) in section 5.

1.4 Report Format

The format of this report first presents system requirements and issues common to the different platforms (airborne, ground-vehicle and man-portable). This section is followed by specific discussions on each platform, and conclusions. The individual sections include the following: section 2 describes the functional requirements of the GPS/INS system to support the proposed UXO requirements; section 3 discusses positioning and navigation issues driving the design of the GPS/INS system and integration with other sensors, in particular the GPR system; section 4 analyzes and compares commercially available GPS and INS instruments suitable for use in UXO detection; sections 5.1 through 5.5 include analysis of the positioning and navigation issues discussed in section 3, as well as additional issues relating to the selection and use of the proposed GPS/INS instruments; section 5.6 distinguishes between the GPS/INS requirements for the different platforms (airborne, ground and man-portable) and recommends a hardware and software configuration for each platform; section 6 discusses requirements and recommendations for the moving map display software needed to support the GPS/INS navigation; and section 7 summarizes the conclusions of the report.

1.5 Conclusions and Recommendations

This System/Design Trade Study has concluded that extremely accurate positioning systems are required if maximum utility is to be made of advanced technology sensor systems. This is particularly true with GPR, where the classification of ordnance or non-ordnance is highly dependent on the accurate imaging of the system. The technologies being developed at present include GPR, magnetic and infrared sensors, and several means of integrating the multisensor data; all need accurate positioning systems. This study has shown that positioning technologies having the potential to provide high-accuracy (0.01m - 0.02m), high-rate positioning are available and include dual-frequency GPS technology integrated with INS technology.

It is recommended that the Government pursue the development of high-accuracy (0.01m - 0.02m) high-rate positioning systems. This can be accomplished by integrating GPS and INS in order to optimize the technologies available for identification, classification and remediation of FUDS contaminated with UXO. It is further recommended that the components of this high-accuracy system consist of the hardware and software identified in section 7.

2.0 FUNCTIONAL REQUIREMENTS

Navigation and sensor technologies available on the market for detection, mapping and remediation of hazardous materials have not yet been developed to the level that can be directly adapted to the UXO detection, mapping and remediation program. For instance, high accuracy (~.05m), high rate continuous GPS/INS positioning necessary for the GPR operation is not available on the market today. The technology components, however, for achieving this high accuracy, high rate positioning are available. These components need integration and testing before they can be directly adapted to the UXO detection, mapping and remediation program. The commercial markets offer a large variety of GPS and INS products and services with various levels of price, performance, accuracy and ruggedness under different operational environments. The need to accurately locate the UXO items (time and position tagging) for detection purposes and efficient remediation efforts places special navigation requirements for the different sensors used on the multisensor platform. This situation created the need for a System Design Trade Study to determine the optimum navigation systems for airborne, ground-vehicle, and man-portable platforms.

Navigational data will support UXO detection by providing quasi real-time (i.e., within 1-2 minutes) information suitable for tracking the sensor system as it traverses the survey site. This data will also support quasi real-time and post-processing of the sensor data (with the GPR being the most stringent). Of significance is the fact that the navigation system operates in a relatively hostile environment. This includes electro-magnetic interference (EMI) from the GPR and any local transmitters (e.g., TV, radio, aircraft radar), transmission path obstructions such as trees cutting off GPS satellite signals, vibration and flight turbulence.

The requirement for GPS/INS positioning in the UXO-ATD Program is threefold:

- Navigation of the moving platform.
- Quasi real-time positioning for sensor calibration.
- Indexing of the sensor data to positioning for post-processing.

The navigation requirements of the UXO detection system are driven by the necessity of accurately locating buried objects at the surveyed site. The sensors used to locate the buried objects (including the GPR system) must perform a complete coverage of the surveyed area. This is accomplished by moving the sensors along predefined survey lines. The separation of these survey lines and the spacing between discrete sensor data points are determined by the

sensor characteristics. For the GPR, for instance, the ideal separation of data points, both in line and between adjacent lines, is between 1/12 and 1/4 of the shortest wavelength of radar energy to support coherent focusing of the energy return information. Accurate positioning information is also required for calibration to maintain the accuracy of the sensor itself as the survey is performed.

High accuracy quasi real-time positioning is required to calibrate the GPR for a variety of parameters before surveying a particular site. The quasi real-time positioning will allow the field operator to process the GPR data with an approximate one minute delay, to evaluate the quality of the GPR data and, if necessary, to make adjustments to the parameters controlling the GPR operation.

The final role of GPS is to index the GPR data with position information for post-processing. Positioning at rates up to and including the GPR data rates will result in more accurate GPR data post-processing. This role of the GPS system alone does not necessitate GPS position information in real-time. GPS position information is only required for post-processing. As mentioned above, quasi real-time GPS positioning is required only for GPR calibration.

All of the above roles call for uninterrupted GPS/INS positioning at 10-90 Hz rates with an accuracy at the .05 - 0.15m range. Section 5.1 contains descriptions of the accuracy, the data rate requirements and their relationships for all three platforms (airborne, ground and man-portable).

This study was conducted taking into consideration that the solutions to meeting navigation requirements should maximize use of Commercial Off the Shelf (COTS) products and, where possible, minimize the need for new technology or equipment development.

3.0 DISCUSSION OF POSITIONING AND NAVIGATION ISSUES

The positioning and navigation issues that will be addressed are the following:

1) Interference between GPS and GPR;
2) Slow GPS standard data rates;
3) Integration of GPS/INS for uninterrupted position information when GPS signals are not available.

The effects of these issues on the different platforms are described in sections 5.1 through 5.5.

3.1 Interference Between GPS and GPR

High accuracy cm-level positioning in both real-time and post-processing requires use of dual-frequency (L1 and L2) carrier phase measurements. The carrier phase measurements are accurate at the mm-level; however, these measurements lack the geometric strength required for the cm-level positioning of the moving GPS receiver. This is the result of the inherent integer ambiguities affecting the carrier phase measurements. Real-time and post-processing cm-level positioning requires resolution of the integer ambiguities affecting the carrier phase measurements (see Appendix A).

Real-time ambiguity resolution is based on a small number of measurements. Consequently, the noise and the systematic errors affecting the measurements will be at the few cm-level. Therefore, the moving GPS receiver should be able to operate in a moderate noise environment. For this reason interference tests between the GPS and the GPR systems were conducted between September 17-21, 1994, at Jefferson Proving Ground in Madison, Indiana. The results of those tests are described in section 5.6.1. The GPR system used in those experiments was designed for airborne applications. The airborne GPR systems operate in the frequency domain (step-chirped system) which makes it possible to transmit high power over a specified range of frequencies. With high power transmissions the S/N ratio of the returned signals is adequate to differentiate them from the background noise.

When the radar was transmitting at approximately ±10 MHz of the frequencies whose third harmonics are the L1 (1575.42 MHz) and L2 (1227.6 MHz) GPS frequencies, the tracking of the GPS signals was interrupted completely. The operation of the GPR used in these experiments did not allow complete deactivation of the interfering frequencies. Its operation allowed only minimization of the time allocated for the transmission of those frequencies. When this time was minimized, the GPS receivers were able to track the L1 signals for all of the satellites in view and the L2 signals for only 2 or 3 out of the 7 or 8 available satellites.

The L2 is a weaker signal and because of Anti-Spoofing (AS) the L2 pseudo ranges and carrier phases are recovered through cross-correlation. Cross-correlation is a noisier process and as a result, the tracking of the L2 signal is more difficult in a noisy and interfering environment. Missing L2 data for most of the satellites will be detrimental to high accuracy positioning both in real-time and in post-processing. To solve this problem the GPR should be equipped with filters that will eliminate completely the transmission of the interfering frequencies. (See section 5.6.1.)

3.2 Slow GPS Standard Data Rates

The data rate requirements for calibrating the GPR system in real-time, and for indexing the GPR data with position information for post-processing are in the range of 10 to 90 Hz (section 5.1). The commercial dual-frequency GPS receivers available on the market today are capable of providing data (pseudo ranges and carrier phases) at a rate of 2 Hz (i.e., twice per second). One solution to this problem is to use doppler and doppler rates to predict the position of the moving GPS receiver at the 10 to 90 Hz rates. The success of this solution depends on the ability to model the dynamics of the moving GPS receiver during the interpolation interval using doppler and doppler rates.

If the dynamics of the moving GPS receiver cannot be modeled with doppler and doppler rates, then it may be possible to modify the GPS receivers to output the GPS data at their internal measuring rate which for most receivers is in the order of 50 Hz. Having GPS data at a 50 Hz rate will allow accurate GPS positions tobe calculated. This rate, however, will not be adequate for all of the GPR requirements (section 5.1). Note that at these high rates, the GPS observations will be much noisier. A third approach, which is the recommended approach, is to integrate the GPS system with an INS system, which will provide not only the required 90 Hz rates but also navigation during the periods when the GPS signals are not available due to obstructions.

3.3 Integration of GPS/INS for Uninterrupted Position Information

Integration of GPS and INS will ensure uninterrupted positioning in quasi real-time, and in post-processing. The positioning accuracy during periods when GPS measurements are not available depends on the accuracy of the INS and on the length of time that GPS measurements are not available. For instance, a low-cost INS (e.g. LN-200 ~$40,000) will provide accuracies at the 0.5m to 1.0m level in post-processing (smoothing) and 3.0m to 6.0m in real-time (filtering), when the GPS signals are obstructed for about 3 minutes (Figure 9). However, a high quality INS (e.g. LN-100 ~$100,000) will provide accuracies at the 0.01m to 0.05m level in post-processing (smoothing) and 0.1m to 0.2m in real-time (filtering) when the GPS signals are obstructed for the same period (Figure 10). When the GPS signals are not available for longer periods, the positioning information degrades exponentially in both real-time and post-processing with a lower rate of degradation in post-processing due to smoothing. Quasi real-time processing will allow smoothing of the INS positioning. For the calibration of the GPR only quasi real-time positioning is required, thereby making it possible to provide smoothing accuracies for GPR calibration in quasi real-time.

Integration of GPS with INS is very important for the airborne platform because it will provide the required higher positioning rates of 10 to 90 Hz without any need to modify the GPS receivers. It will also provide the capability to recover from short losses of lock due to the dynamics of the airborne platform. Furthermore, the INS system will serve as a backup positioning system to minimize loss of information when GPS signals are not available for any unforeseen reasons.

The INS can also provide for the translation of the GPS antenna's location to GPR antenna phase center. This will allow for more flexibility in mounting the GPS antenna relative to the GPR.

4.0 PERFORMANCE ANALYSIS AND COMPARISONS OF GPS AND INS INSTRUMENTS

4.1 Global Positioning System

High accuracy positioning of airborne platforms both in real-time and in post-processing requires use of dual-frequency GPS receivers. The speed and the effectiveness of high accuracy positioning depends to a large extent on the quality of the dual-frequency GPS receivers. For this reason, the Center for Mapping analyzed the quality of the dual-frequency GPS data for Ashtech, Trimble, and Allen Osborne Turbo-Rogue GPS receivers. Ashtech, Trimble and Turbo-Rogue dual-frequency receivers are the leading brands for commercial dual-frequency GPS receivers on the market today. The noise characteristics of the dual-frequency GPS data from these three receivers have been analyzed to determine the expected number of epochs required for On-The-Fly (OTF) ambiguity resolution. This is the number of epochs required to initialize high accuracy positioning after recovering from losses of lock to the GPS signals. A mathematical model for GPS OTF ambiguity resolution is presented in Appendix A.

4.1.1 Approaches/Characteristics

The following three sections contain the analyses of the Ashtech, Trimble and Turbo-Rogue data on the basis of the instantaneous and average values of the estimated widelane[1] ambiguities. As described in Appendix A, the speed and success of the OTF ambiguity resolution depends on the estimated widelanes, the geometry-free carrier phase combination and their accuracies. The accuracy of the geometry-free carrier phase combination is at the low (3-5) mm level and is about the same for all the GPS dual-frequency receivers. The accuracy of the widelane ambiguities, however, depends on the accuracy of the code pseudo ranges, which is a function of the receiver technology. For this reason, the analysis of the dual frequency GPS receiver is based on the analysis of the estimated widelane ambiguities. The data analyzed was from kinematic surveying in the U.S. (Ashtech in New Jersey, Trimble & Allen Osborne in

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[1] The dual-frequency GPS receivers record pseudo-ranges and carrier phases. The carrier phases have wavelengths of 19 cms and 24 cms. When these two phases are subtracted, the resulting phase is called widelane and has a wavelength of 86 cms. When a GPS receiver locks into a satellite signal, it initializes the carrier phases by assigning an arbitrary number to the initial phase measurements. This number changes only when the GPS receiver loses and regains lock to the satellite signal. Carrier phase integer ambiguity refers to the difference of this arbitrary number from the actual number of wavelengths between the phase center of the GPS antenna of the ground receiver and the phase center of the satellite GPS antenna. When these carrier phase integer ambiguities are related to the widelane, they are called <u>widelane integer ambiguities</u>.

California). The stationary and moving receiver data were collected simultaneously to determine the characteristics of interest in receiver selection.

Analysis of Ashtech Dual-Frequency GPS Data

Figures 1, 2 and 3 show the instantaneous and average widelane values for a stationary and a moving receiver for elevation angles ranging from 10 to 80 degrees.

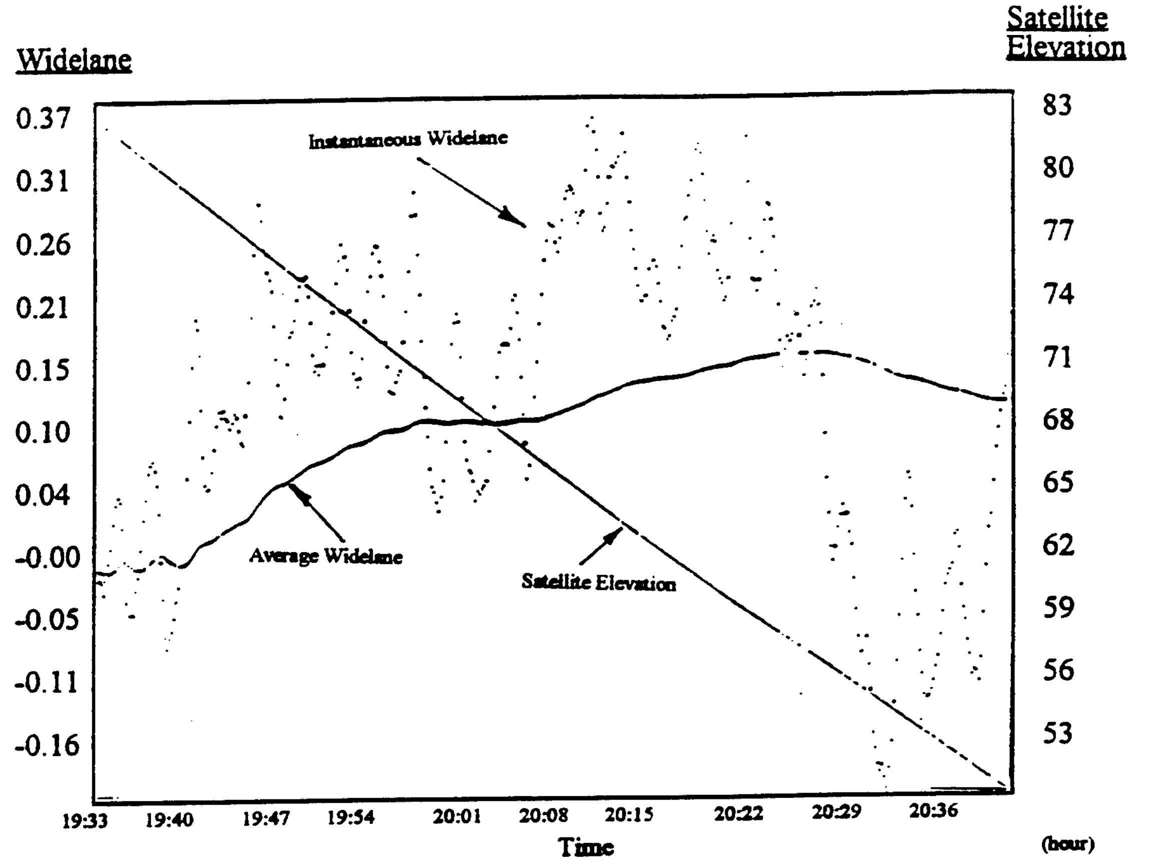
Figure 1 shows the instantaneous and average values of the widelane ambiguities for elevation angles of 53 to 83 degrees. At these high elevation angles the average value of the widelane ambiguities for the stationary receiver varies between 0.0 and 0.21 widelanes. The average widelane variation of the moving receiver at those elevation angles varies between 0.92 and 0.10 widelanes.

It is also clear that the epoch-to-epoch widelane ambiguity of the moving receiver (airplane data used in this analysis as worst case) exhibits a linear trend which seems to be converging at the -.84 value after about one hour of operation. This value is approximately -2 widelanes away from 1.12 value which would require 5 widelanes search (±2 widelanes). This interval search may take several minutes to converge.

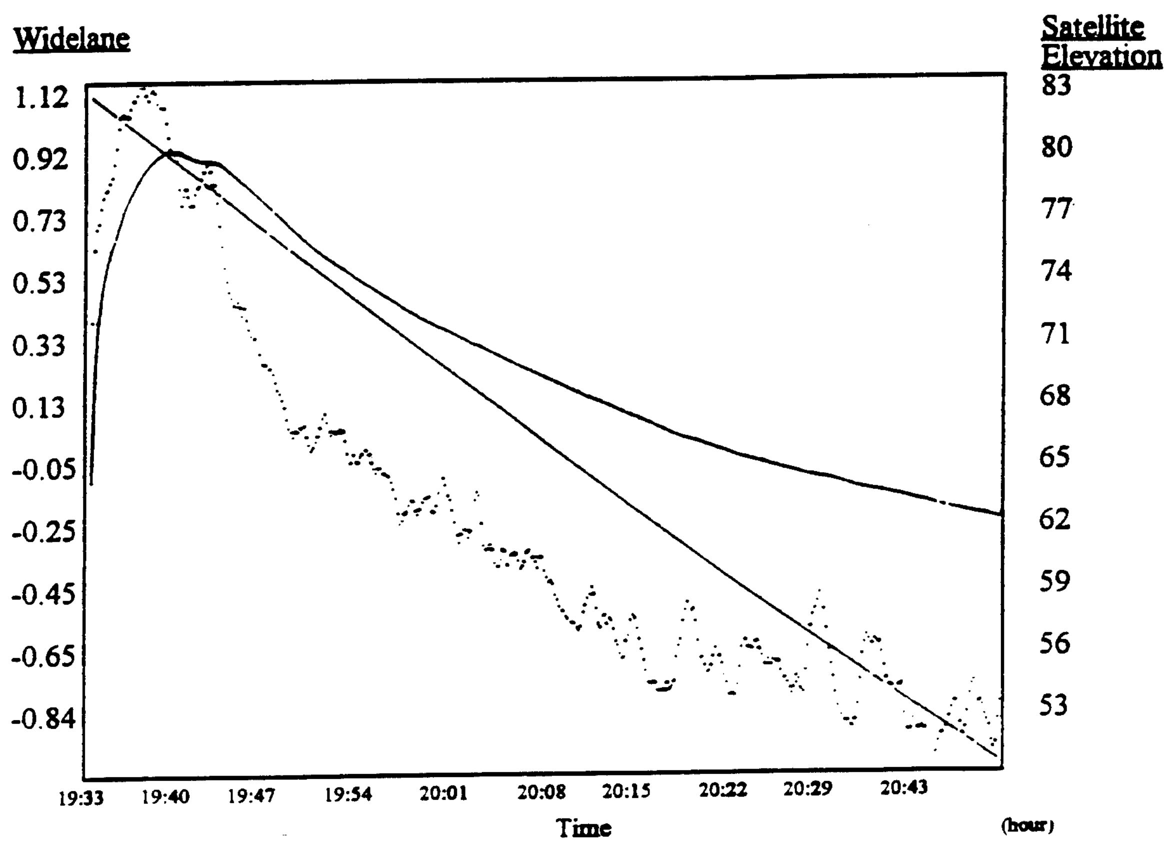
It is evident from figure 1 that the Ashtech data is internally filtered. As a result, the recorded observations are correlated. Therefore, averaging the estimated widelanes will not work because the average will converge to a different value than the actual widelane value as clearly seen in figure 1. In this figure the epoch-to-epoch widelane ambiguities converge at the -.84 value whereas the average widelane ambiguity converges at the -0.05 value. This is the reason why the quality of the Ashtech data is judged on the basis of the epoch-to-epoch estimates of the widelane ambiguities rather than on their average values.

Figure 2 shows the instantaneous and average values of the widelane ambiguities for both the stationary and the moving receivers for elevation angles of 31 to 61 degrees. At these elevation angles the widelane ambiguity of the stationary receiver varies between –0.44 and +0.91 widelanes. For the moving receiver the widelane ambiguity varies between -0.96 and 0.65 widelanes. In this case, the searching interval should be within ±2 widelane which will take several epochs to converge.

Figure 3 shows the instantaneous and average values of the widelane ambiguities for the stationary and the moving receivers for elevation angles of 11 to 34 degrees.

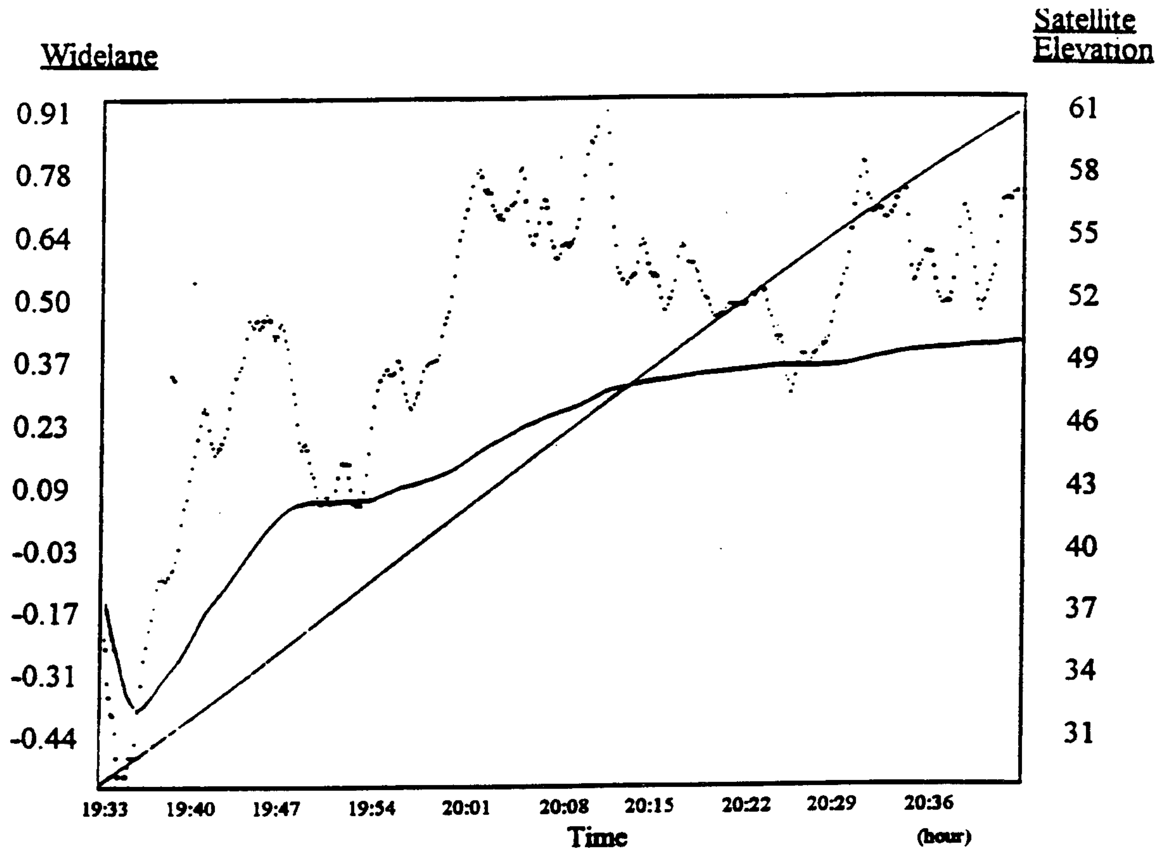


Stationary Receiver and Satellite #22



Moving Receiver and Satellite #22

Figure 1- Instantaneous & Average Widelane vs. Satellite Elevation & Time - Satellite #22



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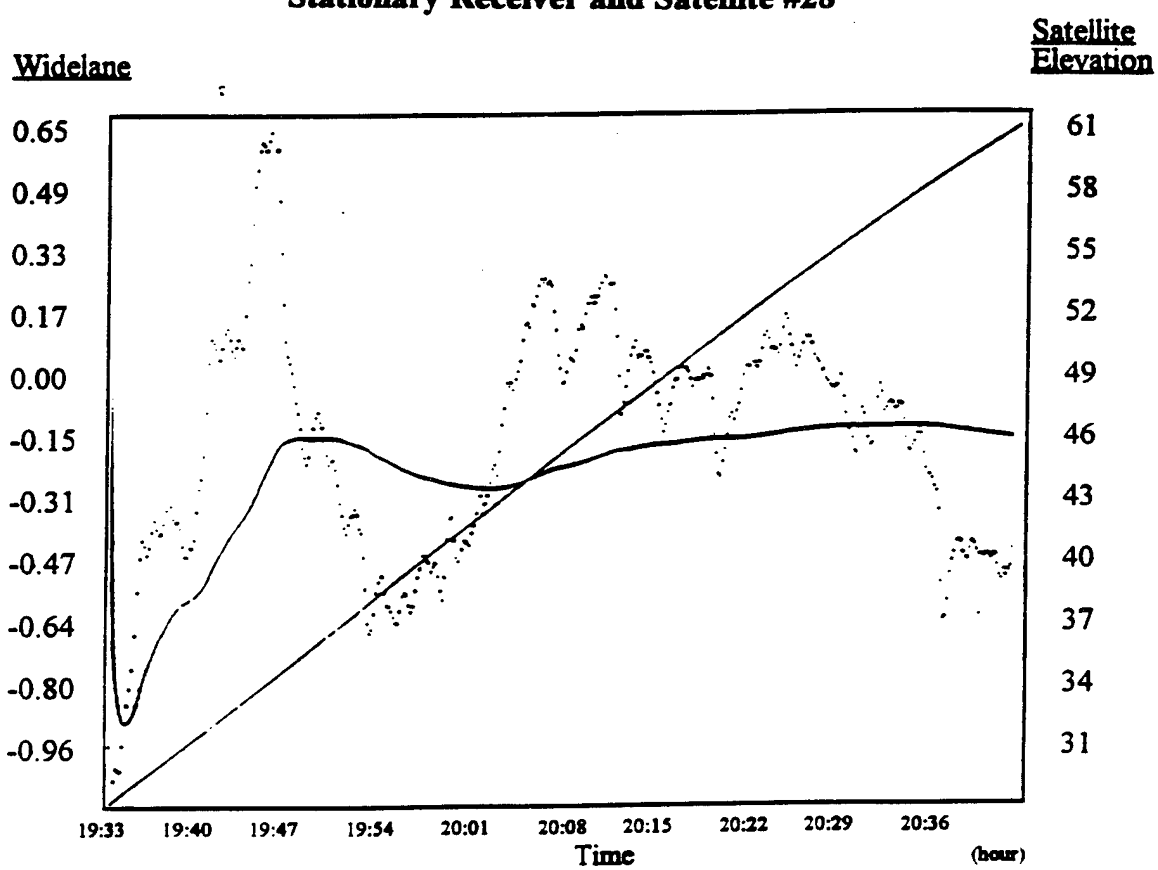
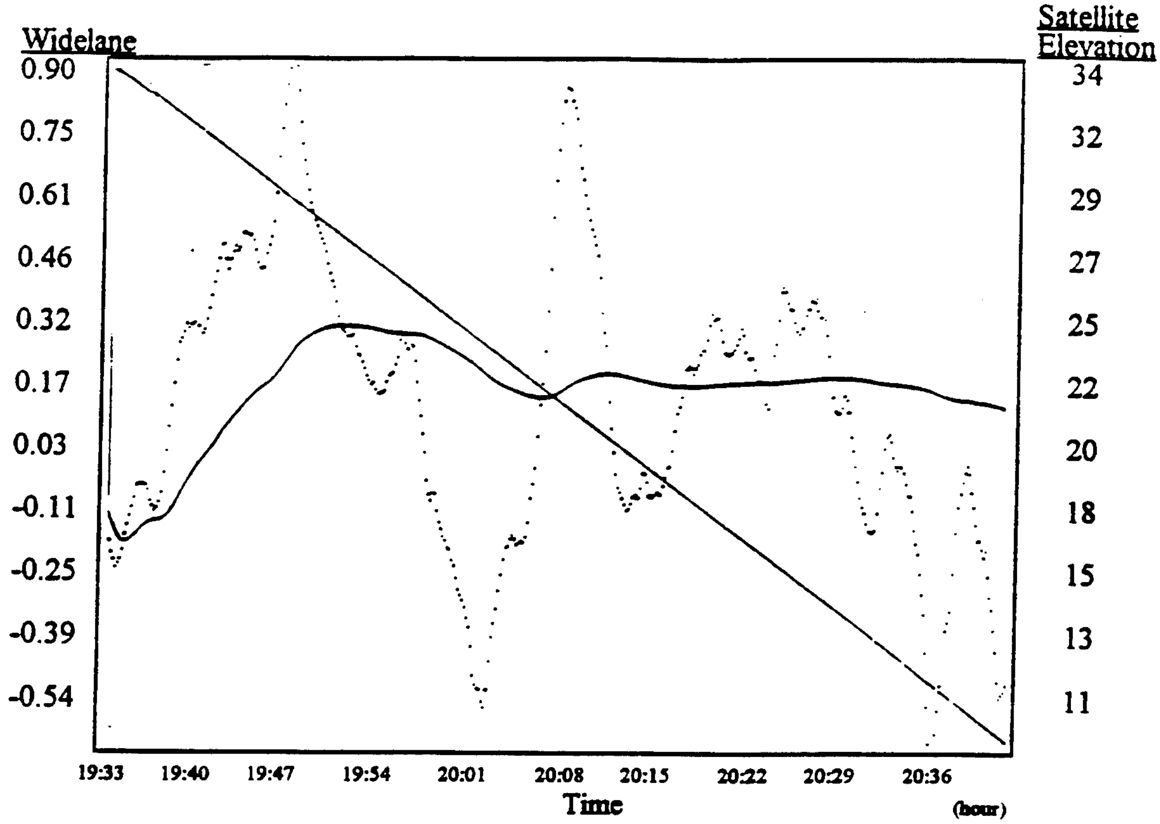
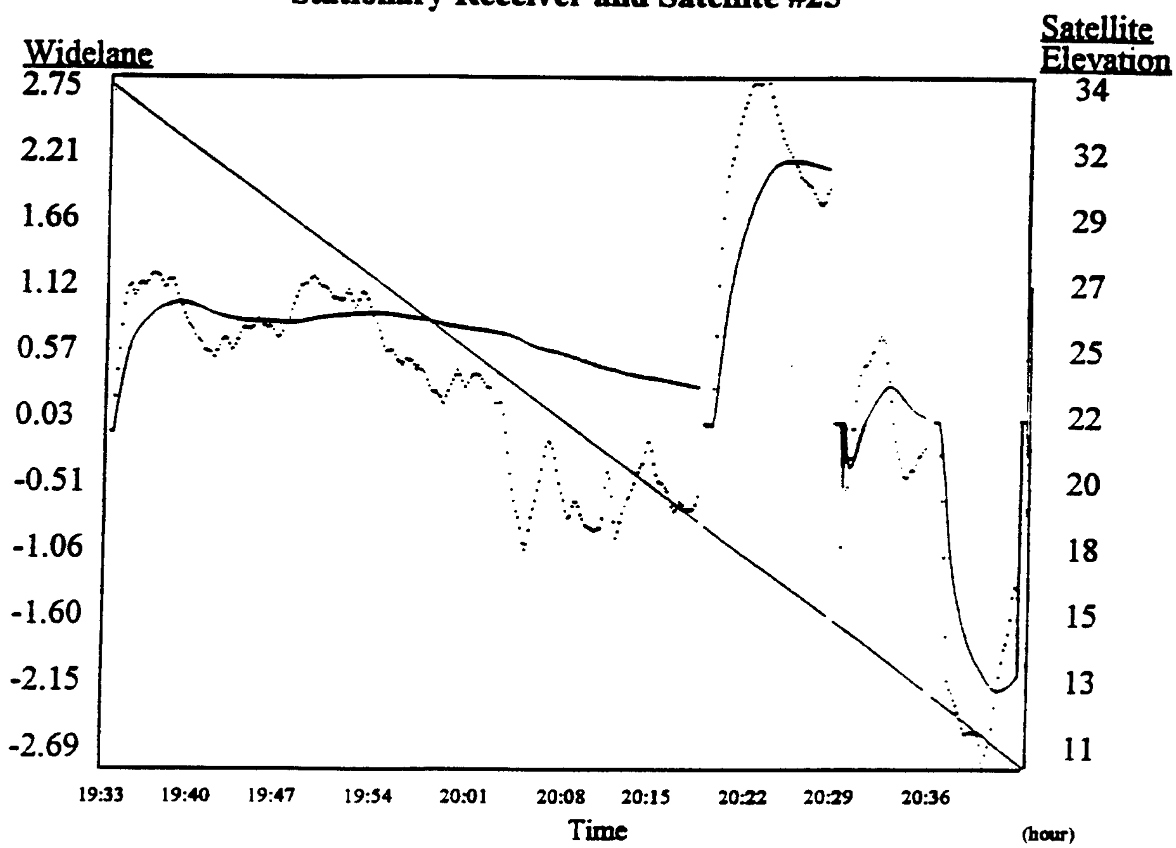


Moving Receiver and Satellite #28

Figure 2 - Instantaneous & Average Widelane vs. Satellite Elevation & Time - Satellite #28



Stationary Receiver and Satellite #25



Moving Receiver and Satellite #25

Figure 3 - Instantaneous & Average Widelane vs. Satellite Elevation & Time - Satellite #25

At these elevation angles the widelane of the stationary receiver varies between -0.54 and 0.90 widelanes whereas the widelane ambiguity for the moving receiver varies between -2.69 and 2.75 widelanes. The reason for the large widelane variations is the presence of cycle slips and the low elevation angles. Furthermore, for elevation angles of 20 to 30 degrees the variation of the widelane ambiguities is about 2 widelanes which will also require a search interval of ±3 widelanes and several minutes to converge.

It is obvious from the above figures that the Ashtech receivers filter their pseudoranges internally to the extent that the widelane ambiguity converges to the correct value after 10 to 20 minutes of continuous tracking. Furthermore, for elevation angles of 25 degrees or less the behavior of the widelane ambiguity is not very good (i.e., there are numerous cycle slips and the ambiguity does not seem to converge to an integer value).

Analysis of Trimble Dual-Frequency GPS Data.

Figure 4 shows the instantaneous and average widelane values for both a stationary and a moving Trimble receiver for elevation angles ranging from about 17 to 84 degrees.

It is evident from this figure that the widelane variation is ±1 for the stationary receiver and ±2 for the moving receiver. Furthermore, the average widelane values of both the stationary and the moving receiver vary by at most 1 widelane for elevation angles above 30 degrees. This is also true for lower elevation angles down to 20 degrees if losses of lock are handled properly. Furthermore, for both the moving and the stationary receiver the average value of the widelane ambiguity converges to the correct value after 1 to 2 minutes of data. Having the widelane ambiguities to an accuracy of one cycle, OTF ambiguity is very fast and effective even with as few as five satellites in view.

Comparing figures 1, 2, and 3 with figure 4 it is obvious that the Trimble data is not filtered and that the average value of the widelane ambiguities converges to the correct widelane value with 1 to 2 minutes of data. This is very important when one or both of the receivers experience frequent losses of lock.

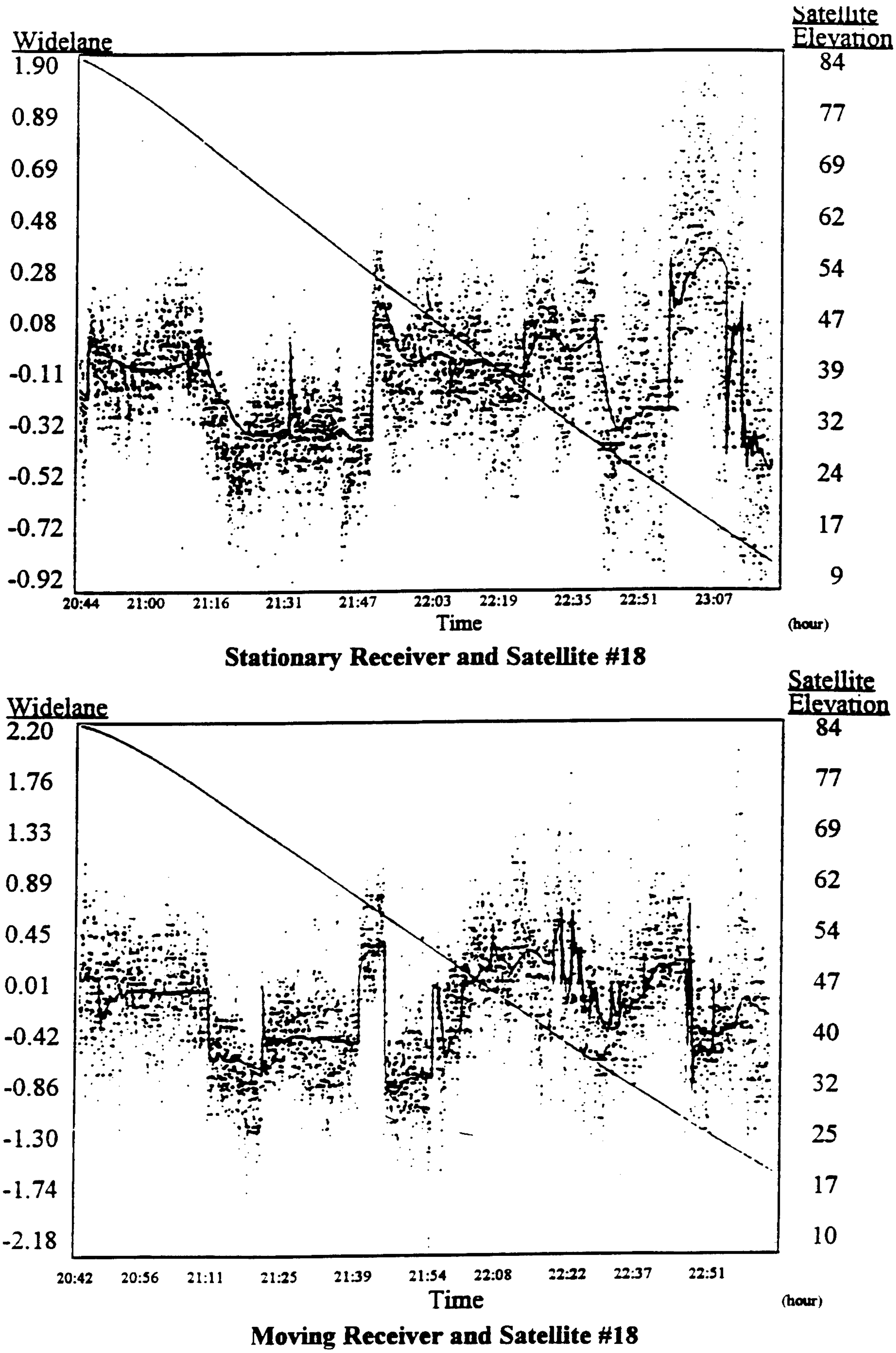


Figure 4 - Instantaneous & Average Widelane vs. Satellite Elevation & Time - Satellite #18

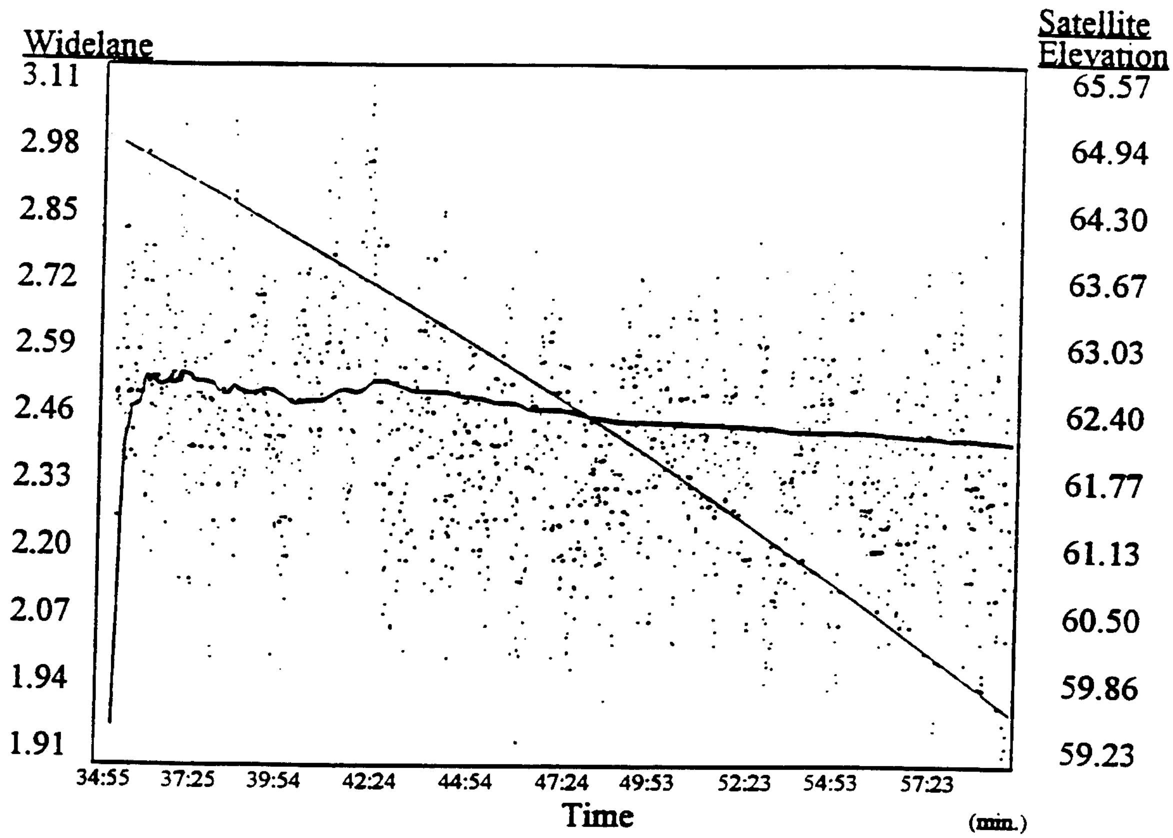
Analysis of Turbo-Rogue Dual-Frequency GPS Data

Figure 5 shows the instantaneous and average values of the widelane ambiguities for both the stationary, and the moving receiver for elevation angles of 59 degrees to 66 degrees. The instantaneous values of the widelane ambiguities vary by 2 widelanes for the stationary receiver and by 4 widelanes for the moving receiver. The average values of the widelane ambiguities, however, vary by 1 widelane for the stationary receiver and by 2 widelanes for the moving receiver. The convergence to the correct widelane ambiguity takes about 2 to 3 minutes of continuous tracking. Therefore, if data is available continuously for 2 to 3 minutes, the widelane can be estimated directly without any need for ambiguity resolution. If loss of lock occurs within that time period, an ambiguity search should be performed before cm-level positioning can be resumed.

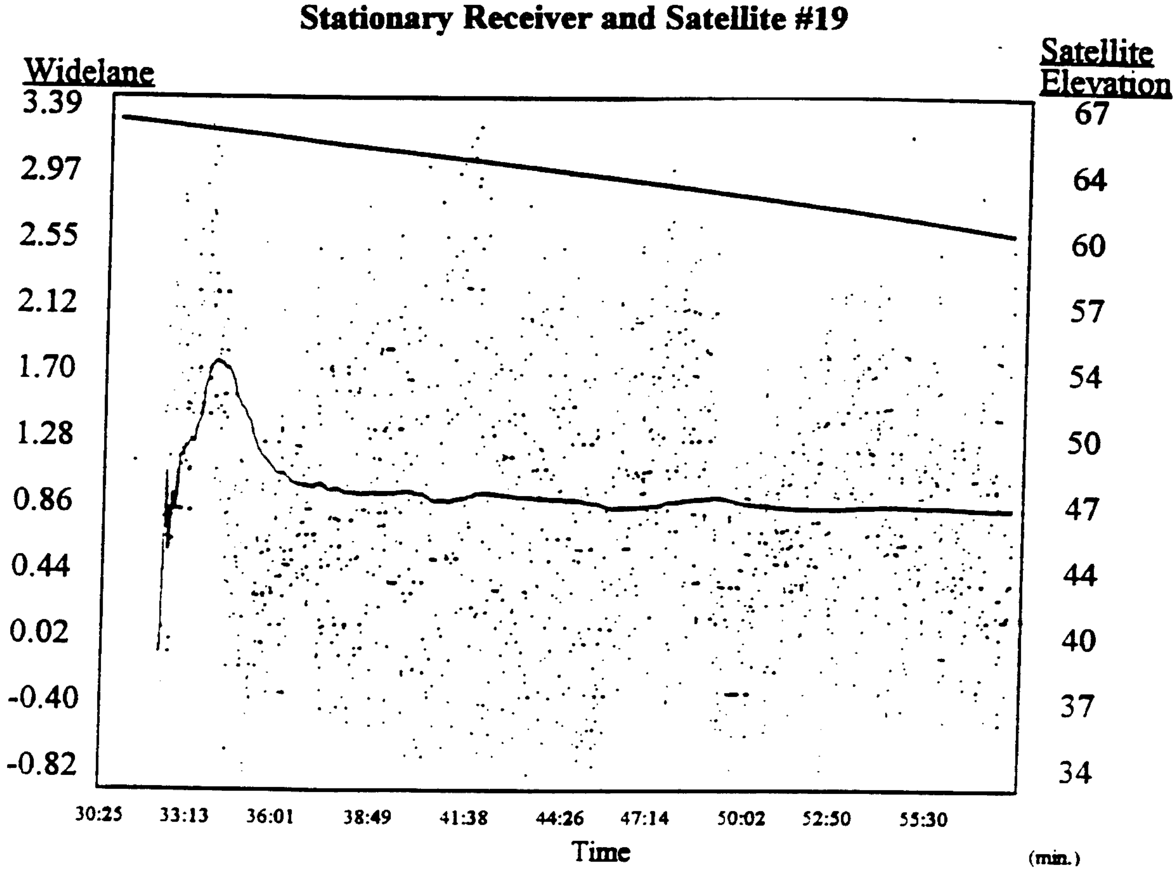
Figure 6 shows the instantaneous and average values of the widelane ambiguities for the stationary and the moving receiver for elevation angles of 35 to 56 degrees. The variation of the instantaneous and average widelane ambiguities for both the stationary and the moving receiver seems to exhibit the same behavior as that for figure 5.

Figure 7 shows the instantaneous and average values of the widelane ambiguities for a stationary and for a moving receiver for elevation angles ranging from about 5 to 50 degrees. The range of the widelane ambiguities for the stationary receiver is 1 widelane for elevation angles above 30 degrees and 2 widelanes for elevation angles of 15 to 30 degrees. The average value of the widelane ambiguity converges to the correct value with 1 to 2 minutes of data. In the neighborhood of cycle slips the average value of the widelane ambiguity varies by 1 widelane for elevation angles above 30 degrees, and by 2 widelanes for elevation angles of 15 to 30 degrees. With only one widelane uncertainty the ambiguity resolution is fast and very robust.

For the moving receiver the instantaneous widelane ambiguity fluctuates by 3 widelanes and the average widelane ambiguity fluctuates by less than 1 widelane, 1 to 2 minutes away from a cycle slip. In the neighborhood of a cycle slip the widelane ambiguity fluctuates by one to two widelanes. Therefore, one minute averaging will yield an uncertainty of one widelane which in turn will warranty fast and robust ambiguity resolution.

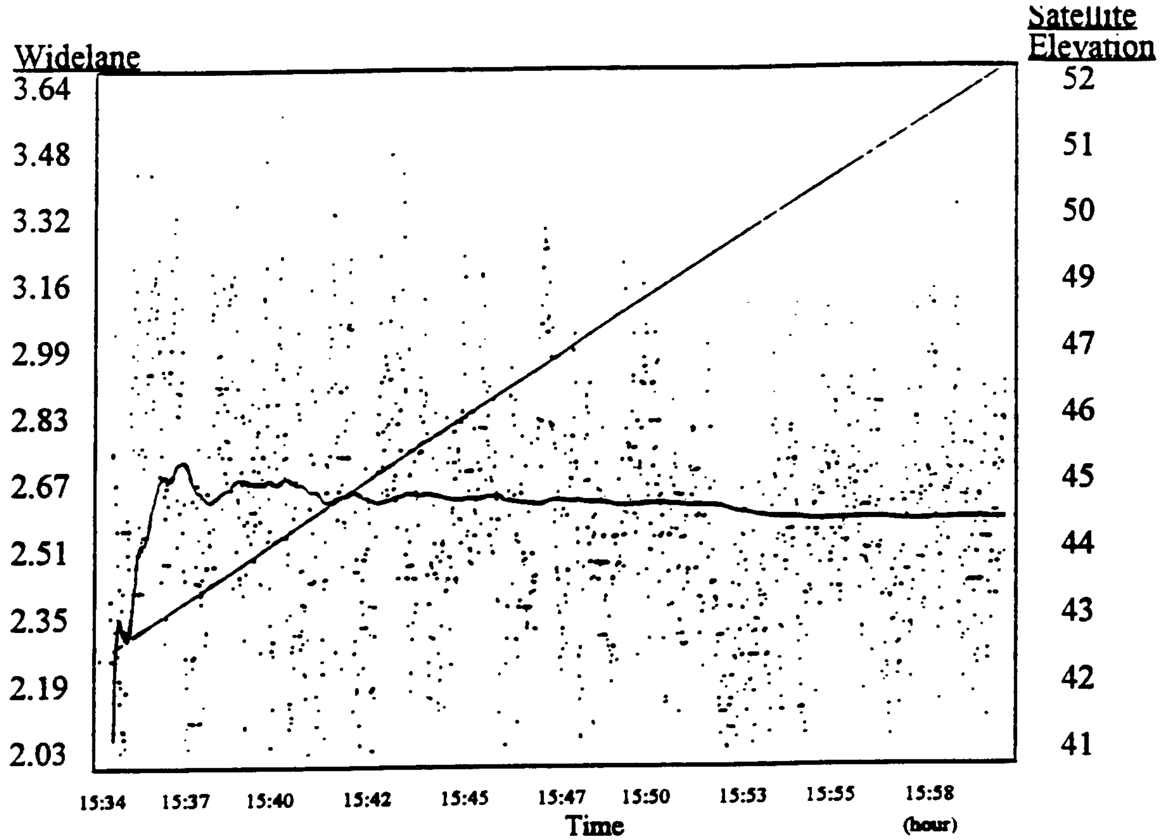


Stationary Receiver and Satellite #19

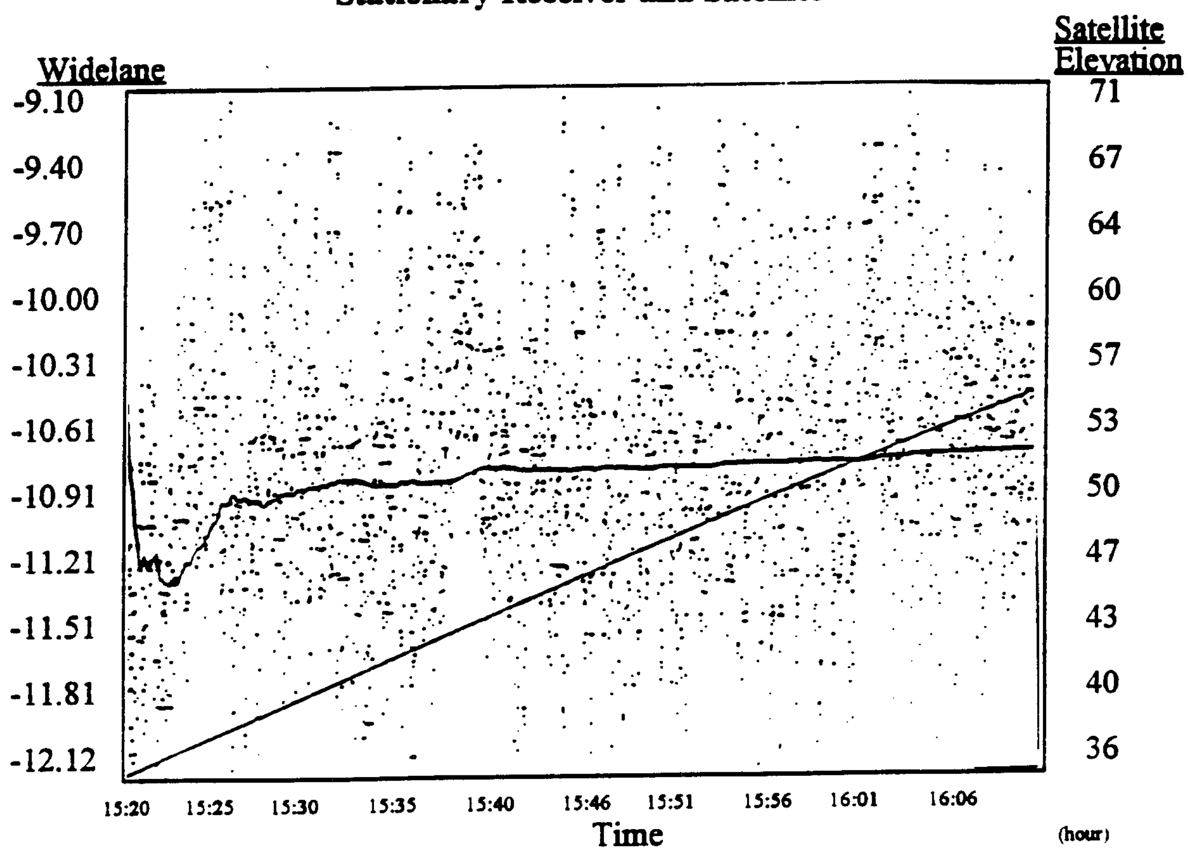


Moving Receiver and Satellite #19

Figure 5 - Instantaneous & Average Widelane vs. Satellite Elevation & Time - Satellite #19

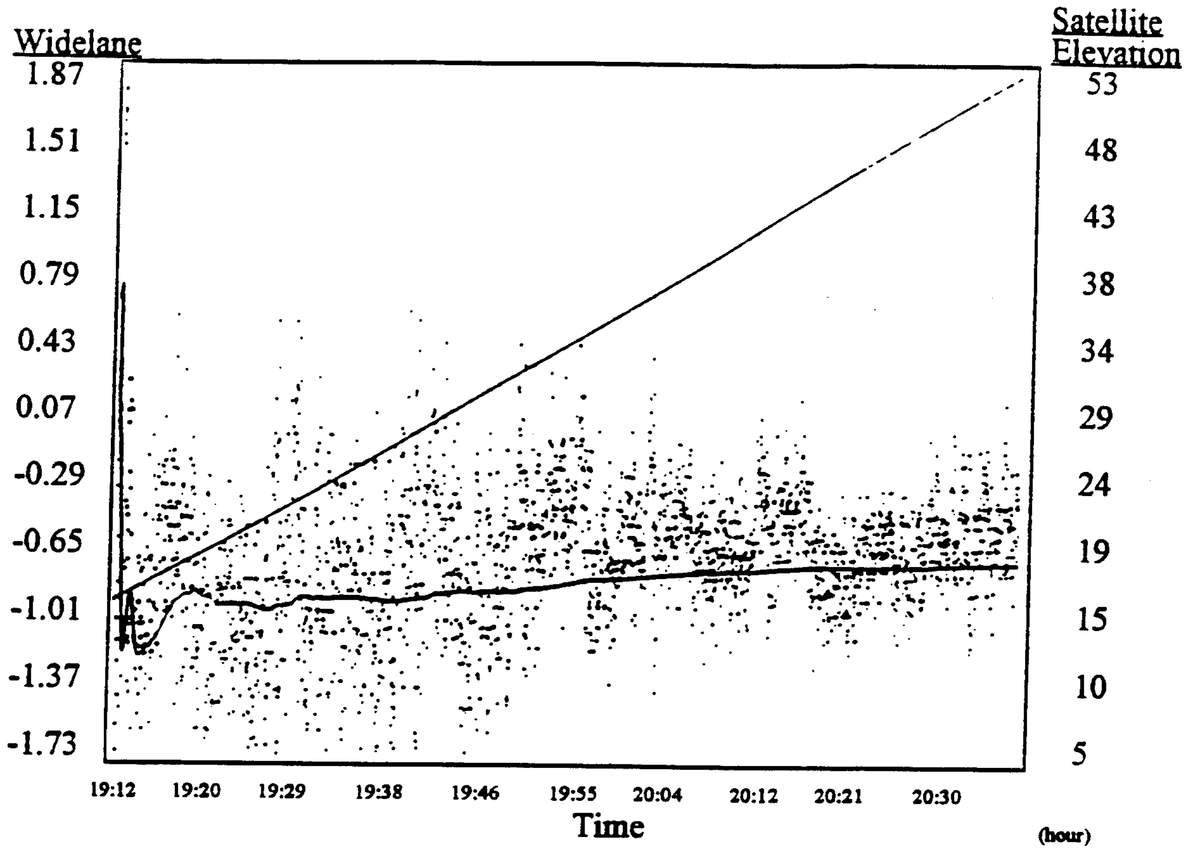


Stationary Receiver and Satellite #2

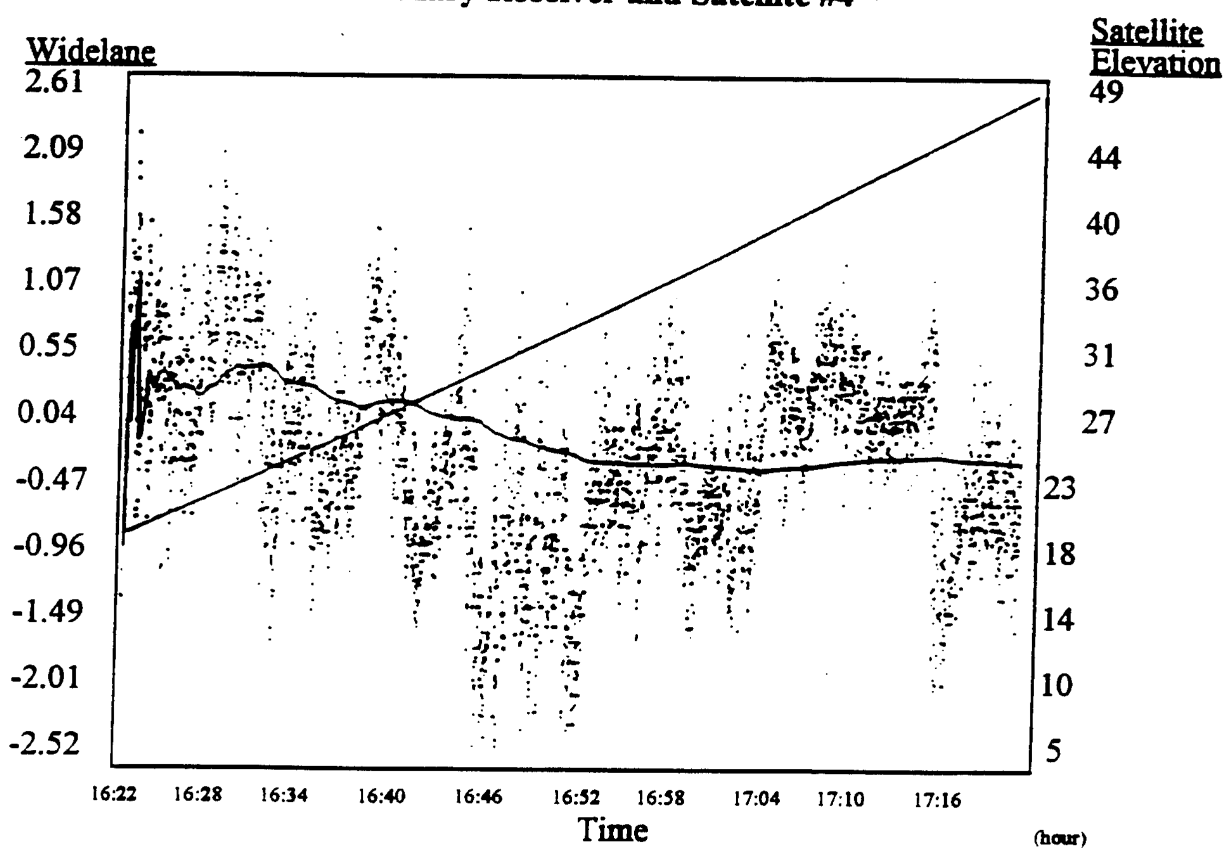


Moving Receiver and Satellite #2

Figure 6 - Instantaneous & Average Widelane vs. Satellite Elevation & Time - Satellite # 2



Stationary Receiver and Satellite #4



Moving Receiver and Satellite #7

Figure 7 - Instantaneous & Average Widelane vs. Satellite Elevation & Time - Satellites #4 & #7

Ground Plane Consideration

For all of the results described in the previous sections the stationary receivers were equipped with a geodetic antenna which is protected with a ground plane. The moving receivers, however, were equipped with an airplane antenna which is not protected with a ground plane. Furthermore, the quality of the data does not seem to be better when the airplane was parked on the taxi way. This suggests that the reason for having worse data from the moving receivers is the absence of the ground plane from the airplane antenna. For the airborne platform an airplane antenna must be used with the understanding that the GPS data will be noisier due to the dynamics of the airplane and the presence of multipath. For the ground and man-portable platforms the moving receiver should be equipped with a geodetic antenna.

4.1.2 Recommendation

The quality of the GPS data from Ashtech, Trimble, and Turbo-Rogue receivers was investigated using instantaneous and average values of the widelane ambiguities. A summary of the results is given in table 1. The speed and reliability to estimate the widelane ambiguities will determine the robustness of the real-time and post-processing GPS cm-level positioning.

From this analysis it is clear that Ashtech receivers filter the data internally. As a result the recorded pseudoranges are correlated, and therefore additional filtering or averaging will not be effective in speeding up the estimation of the widelane ambiguities. Consequently, one should wait until the internal filtering yields the widelane ambiguity to within one cycle. The time it takes for the filter of the moving receiver to converge to 1 widelane uncertainty is 10 to 20 minutes long, which will make it very difficult to recover from losses of lock. For the stationary receiver, however, the estimated widelane ambiguities seem to have an uncertainty of 1 to 1.5 widelanes, which is a good range for OTF ambiguity resolution.

It is also clear from the GPS data analysis that the Trimble, and Turbo-Rogue receivers do not filter their data internally. As a result the instantaneous widelane ambiguities are uncorrelated and they can be filtered or smoothed optimally to yield values with one widelane uncertainty, in which case OTF ambiguity resolution is fast and effective. The time it takes to filter the widelane ambiguities to an accuracy of one widelane is about 1 to 2 minutes for both the Trimble and Turbo-Rogue receivers. From the analysis of Ashtech, Trimble, and Turbo-Rogue GPS data it is recommended that either Trimble, or Turbo-Rogue receivers, equipped with geodetic GPS antennas should be used for the base stations. For the airborne platform, an

airplane antenna should be employed; for the ground and man-portable platforms, a geodetic antenna should be used.

Table 1
Summary of Receiver Comparison

	Ashtech		Trimble SSE		Allen Osborne Turbo-Rogue	
	Stationary	Moving	Stationary	Moving	Stationary	Moving
Low elevation widelane ambiguity (widelanes)	-0.54 +0.90	-2.69 +2.75	-0.92 +1.09	-1.30 +2.00	-1.73 +1.87	-1.49 +2.09
High elevation widelane ambiguity (widelanes)	-0.44 +0.91	-0.96 +0.65	-0.72 +0.48	-1.30 +0.89	-1.37 +0.43	-2.52 +1.07
Average widelane (widelanes)	N/A due to internal filtering	N/A due to internal filtering	+/-1	+/- 2	+/-2	+/-2
Convergence	10 - 20 minutes		1 - 2 minutes		2 - 3 minutes	

4.2 Inertial Navigation System

Aiding of GPS positioning with inertial navigation is needed to provide navigation and positioning information during the periods when the GPS signals are not available due to obstructions. Furthermore, accurate image focusing of the GPR requires positions at a rate of 10-90 Hz (section 5.1). The commercial GPS receivers available on the market today provide positions at a rate of at most 2 Hz. A combination of GPS with an INS is capable of providing positioning information at a rate of up to 200 Hz, which more than covers the requirements of the GPR.

During the reporting period the Center for Mapping conducted a covariance analysis to establish the accuracy requirements of INS for high accuracy positioning rates between GPS fixes, and high accuracy positioning during the periods when the GPS signals are not available due to obstructions. In this covariance analysis it was assumed that 0.03m level GPS positions will be available at a rate of 1 position every 10 seconds, with missing GPS data for periods of up to 5 minutes. During GPS outages (periods with missing GPS data due to obstructions), the navigation of any of the platforms will rely on an INS, corrected with the error models as revised from the last GPS updates.

Approaches/Characteristics

For the purpose of this analysis it is sufficient to assume that the system has nominal, essentially constant motion with respect to the earth's surface, which means that the latitude, longitude, and height rates are zero. For covariance analysis, this assumption does not cause substantially different results from more realistic assumptions of motion. The sampling rate is assumed to be 2 Hz, and the total time interval for the analysis is arbitrary since the Kalman filter is a recursive filter. Appendix B provides a discussion on the mathematical models used in evaluating inertial navigation capabilities.

The INS for this analysis was assumed to be a strapdown system oriented with ring laser or fiber optic gyros; the accelerometers are usually of force-rebalance type. Table 2 lists the types and the values of the errors considered in the covariance analysis. These errors are assumed to cover, or dominate, the multitude of sensitivities of the instrument in an environment of moderate dynamics and controlled temperatures. The error budget for a particular system is more detailed since it depends on the specific vibration/shock and temperature isolation mechanisms available, as well as the specific idiosyncrasies of the particular sensor. Consideration of more than just the basic error parameters is, therefore, beyond the present scope of this investigation. In addition, the unique calibration problems and the dynamic motion induced gyro errors of strapdown systems are ignored as they are also to some extent mission dependent. As mentioned above, the GPS position updates are taken as direct observations of position with the errors modeled as white noise. The initial errors in the states were assumed to be given by the standard deviations corresponding to the values in table 2 for the position and bias states. For the velocity, it was assumed to be 0.005m/sec; and for the orientation angles, it was taken as 8 arc-seconds for the level components and 130 arc-seconds for the heading.

Figure 8 shows the accuracy of the platform positions in east, north and down directions as a function of time. In this figure the GPS positions are assumed to have an accuracy of 0.03m with an update rate of 0.1 Hz (one position every 10 seconds). It is evident from this figure that the accuracy of the INS positions deteriorates exponentially between GPS updates, and that the maximum error between the GPS updates decreases to a steady-state value after about 200 seconds.

Table 2

Parameter Values used in Simulation

IMU(INS)		(LN-100)	(LN-200)
	Accuracy	Medium-High	Low
Accelerometer			
	bias error	25mgal =: 25 μg	200mgal =: 200 μg
	scale factor error	120 ppm	300 ppm
	white noise	8 mgal/√Hz	50 mgal/√Hz
Gyros			
	drift bias error	0.003 / √hr	1. / √hr
	white noise	0.0055° / √hr	0.07°/ √hr
Platform Position Updates Using GPS			
	period:	0.1 Hz	0.1 Hz
	precision:	3 cm	3 cm

Figures 9 and 10 show the interpolation capability of two types of instruments, one of low accuracy (i.e., LN-200) and one of medium to high accuracy (i.e., LN-100) system. The low accuracy system, which is also a low cost system (~$40,000), can maintain an accuracy of ~.5 meters in free-inertial (i.e., filtering) mode and ~.1 meter in smoothing mode for about one minute without any GPS fixes. For longer GPS outage periods (e.g., 5 minutes or more) the low cost system can maintain an accuracy of 21.28 meters in free-inertial (i.e., filtering) mode and 3.45 meters in smoothing mode. The high accuracy systems (higher cost, ~$100,000), can

maintain an accuracy of .569 meters in free-inertial (i.e., filtering) mode and an accuracy of .1 meter in smoothing mode when GPS signals are not available for about 5 minutes.

For an airborne system the expected periods of GPS outages will be in the order of several seconds. Therefore a low cost, low accuracy inertial system will provide the .07m accuracy requirements in both quasi real-time and in post-processing.

Recommendation

From the covariance analysis for the integration of GPS with INS, it was evident that ~0.1m navigation without GPS is possible for periods of up to 1 minute (smoothing mode) with a low accuracy system and for periods up to 5 minutes with a high accuracy system. As described in section 5, the LN-200 (low accuracy) system is recommended for the airborne and the man-portable platforms, and the LN-100 (high accuracy) system is recommended for the ground platform.

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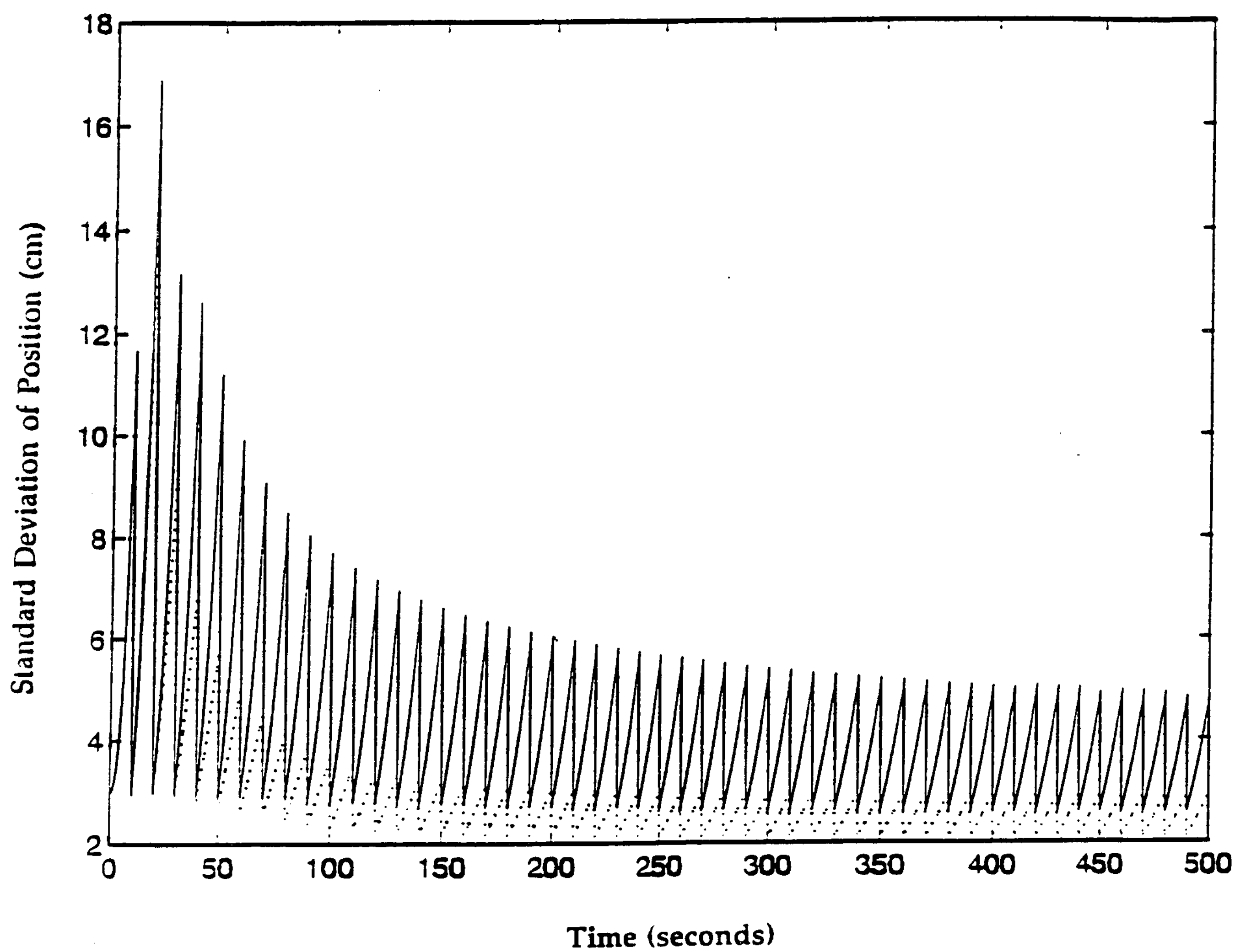

Figure 8 - Position Errors for GPS Outages of 10 Seconds
(East, North and Down Directions)

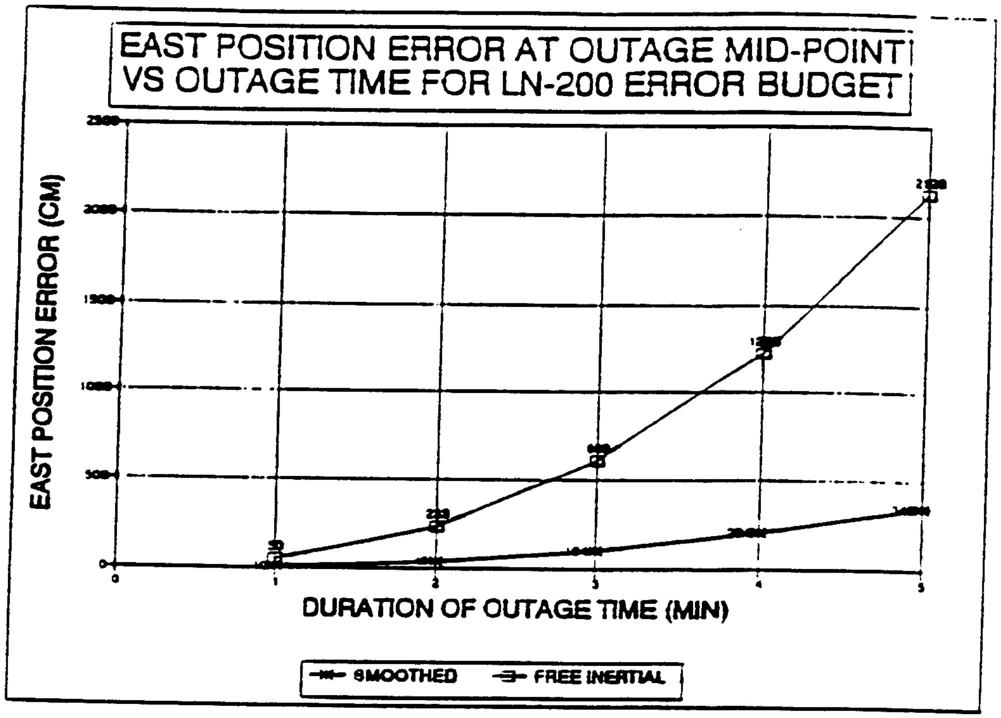

Figure 9 - East Position Error at Outage Mid-Point vs Outage Time for LN-200 Error Budget

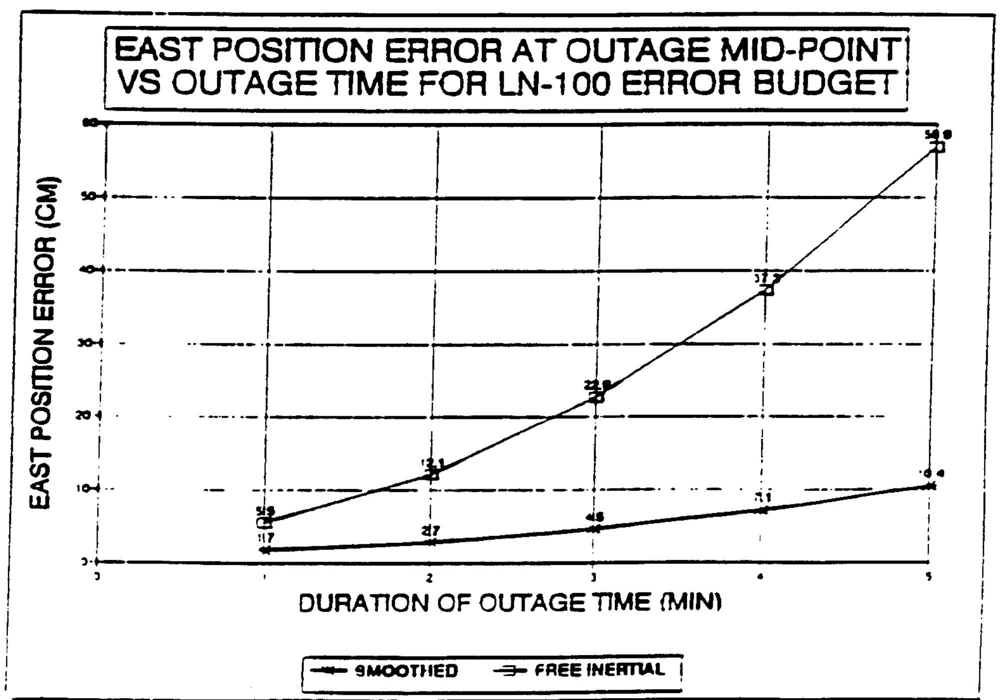

Figure 10 - East Position Error at Outage Mid-Point vs Outage Time for LN-100 Error Budget

5.0 SYSTEM/DESIGN TRADE STUDY PARAMETERS

5.1 Accuracy and Update Rates

The GPR drives the navigation requirements for all of the three platforms (airborne, ground, and man-portable[2]). For all platforms the objective is to produce a data set containing probable UXO locations within a grid of voxels using the raw waveform data.

The radial returns measured from different positions along a survey line may all detect a buried object. These returns will be skewed in time due to the time shift introduced when detecting a buried object from different vantage points on the surface (ground and man-portable platforms) or in the air (airborne platform) which results in a hyperbolic shifting of apparent detection location. Combining multiple-position measured waveforms from the raw data ultimately generates a processed data set, providing net energy return levels at each voxel in the soil, using a process referred to as "focusing". The energy return levels are subsequently processed to produce a map containing the probable UXO site locations.

To perform the focusing of the GPR measurements, it is required to know the location of the platform for all GPR measurements with an accuracy that will allow processing of all the measurements (phases) coherently. The need to know the position for all GPR measurements establishes the navigation rate requirements, and the requirement to process the GPR phases coherently establishes the accuracy requirements as explained below.

Suppose that the radar makes measurements every 5 milliseconds corresponding to 200 Hz rate. The positions of the platform should be known with the same rate. Focusing the raw GPR measurements coherently requires a positional accuracy for each measurement of 1/4 to 1/12 of the smallest wavelength, corresponding to the highest frequency of the transmitted energy. Therefore, for the GPR operating in 50-500 MHz frequencies, the navigation accuracy requirement is between 1/12 (~.05m) and 1/4 (~.15m) of the smallest wavelength (~.60m), corresponding to the 500 MHz frequency. The ~.05m accuracy requirement places a limit on the required rates, since a 200 Hz GPR rate yields a distance between samples of 0.011m (5 x 1600m/3600sec/200 Hz) for a platform moving at 5 miles/hour. Having the positions every 0.011m with an accuracy of .05m does not make any sense, so the navigation rate requirement can be adjusted to 44.44 Hz, which corresponds to .05m platform displacement with a speed of

[1] Only true if the man-portable system uses SAR focusing.

5 miles/hour. Averaging is then used on the waveforms taken within 0.05m spacing, which increases the S/N ratio and the dynamic range. A summary of the data used to determine update rates is given in table 3.

It is evident from the above discussion that the positional accuracy of the moving platform should be between 1/12 and 1/4 of the wavelength corresponding to the highest frequency of the GPR. The navigation rate requirements depend on the GPR measurement rates, the speed of the platform and the provided navigation accuracy. With higher positional accuracies, less GPR averaging will be required, and therefore, potentially more detailed information will be available. The above discussion is valid for time domain, frequency domain (SAR), or hybrid systems, since all of these systems can be thought of as time domain systems through a Fourier transformation.

The position/navigation update rate will correspond to the GPR sampling rate for which the distance between samples is equal to the accuracy of the estimated positions. The GPR samples collected at a higher rate will be averaged.

As mentioned in section 3.2, the commercial dual-frequency GPS receivers available on the market today are providing positions with rates of up to 2 Hz (twice per second). To increase the position rates to the level required for the focusing of the GPR measurements, the GPS system should be integrated with an INS system. This approach will produce the required higher position rates of up to ~90 Hz and will provide navigation during periods when the GPS signals are not available.

Table 3
Data Used to Determine Position/Navigation Update Rates for Different Platforms

GPR Rate	Platform Velocity	Distance between Samples	Focusing Requirement
	(ground)		
200 Hz	5 miles/hour	0.011m	0.05m
44.44 Hz	5 miles/hour	0.05m	0.05m
	(airborne)		
200 Hz	10 miles/hour	0.022m	0.05m
88.88 Hz	10 miles/hour	0.05m	0.05m
	(man-portable)		
200 Hz	1 mile/hour	0.0022m	0.05m
8.88 Hz	1 mile/hour	0.05m	0.05m

5.2 Interference Between GPS and GPR

Interference between GPS and GPR occurs when the GPR is transmitting in the neighborhood (+/- 10MHz) of its third harmonics, which correspond to the GPS L1 (1575.42 MHz) and L2 (1227.6 MHz) frequencies. This interference is a function of the GPR antenna pattern and its relation to the direction of the observed satellites.

As described in section 5.6, the results of the interference experiments between GPS and GPR conducted at Jefferson Proving Ground in Madison, Indiana, showed that the interference between GPS and GPR made it impossible to achieve cm-level positioning. The GPR system used in these experiments was designed for airborne applications, operating in the frequency domain using a step-chirped transmitter and local oscillator to output pulsed continuous wave (CW) signals between 50 MHz and 700 MHz.

The GPR architecture of the airborne system makes it possible to transmit high power over the specified range of frequencies, and as a result, the S/N ratio of the returned signals is high enough to differentiate them from the background noise. With the high power

transmissions of the frequency domain airborne systems, interference with GPS is more likely as compared to the lower power transmissions of the time domain systems employed for the ground and man-portable systems.

5.3 Environmental Factors

The GPS satellites transmit spread-spectrum signals consisting of two components: Link 1 (L1), at a center frequency of 1575.42 MHz; and Link 2 (L2), at a center frequency of 1227.6 MHz. These signals can be obstructed by thick foliage, buildings, etc. As a result, GPS navigation may not be possible close to high trees with thick foliage, close to high buildings, or close to other obstructions. This will affect both the ground and man-portable platforms.

Since many UXO sites contain high trees it is likely that in many cases GPS navigation will not be possible. In these cases an INS which is integrated with the GPS system will provide the navigation for the ground and man-portable platforms.

The errors affecting the INS positions grow as the integral in time of the accelerometer, gyroscope, initial tilt, and heading errors (section 4.2). As a result, if GPS positions are not available for a certain period of time the INS position errors will grow beyond the level required for successful processing of the GPR measurements. In these cases the ground and man-portable platforms need to come to a complete stop and perform Zero Velocity Updates (ZUPs) to correct the INS navigation errors.

The time interval between ZUPs depends on the required positioning accuracy, the quality of the INS, and the length of time during which GPS positions are not available. For instance, to achieve positioning accuracies of .05m or less with a LN- 100 INS system, and without any GPS updates, the interval between ZUPs should not be more than 3 minutes (figure 10).

For an airborne platform, if the antenna is properly positioned, obstructions are not a problem during regular operating sessions. However, in an airborne environment, electromagnetic radiation may interfere with the weaker L2 GPS signal, which may cause interruption of the high accuracy positioning (section 5.6).

5.4 Tropospheric Delay

The delay experienced by radio waves when propagating through the electrically neutral atmosphere is called tropospheric delay. This propagation delay is generally split into two components, called hydrostatic (or dry), and wet, each of which can be described as a product of the delay at zenith and a mapping function, which models the elevation dependence of the propagation delay. This modeling is very accurate (~0.01-0.02m) for ground stations.

When operating in an airborne environment the model must accurately represent the relative tropospheric delay caused by this altitude difference. The troposphere extends from the ground up to an average of 11 kilometers. The troposphere within a few kilometers from the ground is considered to be the boundary layer. The boundary layer profile is affected by wind, evaporation, heat transfer, pollutant emissions and terrain-induced flow modification. The boundary layer thickness changes in time and space from a hundred meters to a few kilometers. As the ground warms and cools, the boundary layer profile changes, which in turn changes the temperature and humidity gradient with altitude. Thunderstorms can also modify the boundary layer within minutes. These and other effects reduce significantly the accuracy of the tropospheric models making it very difficult to perform high accuracy (~.05m) level positioning. Therefore, for the airborne platforms the weather conditions play a very important role in high accuracy positioning. Experiments should be conducted to establish the weather conditions that will allow high accuracy positioning when surveying with an airborne platform.

5.5 Temperature, Shock and Vibration

Temperature, shock and vibration have different values and different behaviors for the airborne, ground, and man-portable platforms. The recommended LN-100 and LN-200 Inertial Measurement Units (IMUs) have been tested for low and high temperatures and for different shock and vibration parameters. Table 4 shows the environmental operation parameters for the LN-100 and LN-200 IMUs.

Table 4
Environmental Characteristics
of LN-100 and LN-200

	LN-100	LN-200
Temperature	-54 C to +71 C	-54 C to +85 C
Vibration (random)	17.4 grms endurance	17.9 grms endurance
	8.1 grms performance	11.9 grms performance
Shock	21g /25Hz	4.2g/100HZ to 1186g/1500Hz

Both the LN-100 and the LN-200 IMUs have been built for the Department of Defense and have been tested for airborne rotary Wing, Uninhabited Fighter, and Uninhabited Transport environment. For the airborne platform (helicopter) the random vibration is in the order of 2.5 to 3 grms, and under moderate turbulence the shock is in the order of 5g over frequencies of 10 to 40 Hz. The temperature range for the airborne environment is well within the operational characteristics of both the LN-100 and LN-200 IMUs.

The recommended Allen Osborne and SSE dual-frequency GPS receivers have been tested for low and high temperatures and for shocks and varying frequencies. Table 5 shows the environmental operational parameters for the Trimble SSE and the Allen Osborne Turbo-Rogue GPS receivers.

In the ground platform environment the shock and vibration characteristics are very different than those in the airborne environment. However, the shock and vibration operational range of both the INS and GPS instruments is very wide, and therefore, it is not anticipated to have any problems in navigation, especially when shock and vibration mounting is used.

Table 5
Environmental Characteristics for GPS Receivers

		Turbo-Rogue	Trimble SSE
Temperature	(Antenna)	-40C to +70C	-40C to +75C
	(Receiver)	-20C to +50C	-20C to +55C

5.6 Results and Recommendations

Results and recommendations for the different platforms are presented separately. As part of the conceptual design for the Airborne Navigation System, the results of experiments to test interference between GPS and the GPR at Jefferson Proving Ground, have been included.

5.6.1 Conceptual Design of the Airborne Navigation System

The airborne system consists of two components (figure 11); the base and the airborne components. The base component consists of one computer, one dual-frequency GPS receiver, and a radio receiver/transmitter, all of which are enclosed in a waterproof container for continuous use in outdoor exposed environments. The base component contains a power amplifier which allows operation of the system over distances of up to 20 miles. The airborne component consists also of one computer, one dual-frequency GPS receiver integrated with an INS, and a radio receiver with an antenna. The base station provides the differential signals for high accuracy differential GPS positioning. Appendix C lists the recommended hardware for the different platforms.

The base and airborne GPS observations will be processed together with the INS measurements by the airborne computer to estimate the positions of the airborne platform. These positions are used to focus the GPR measurements in near real-time (~1 minute delay). The results of the focusing will be shown on the airborne computer display to allow the operator to calibrate the GPR operating parameters.

As explained above, the required accuracy to process the GPR data coherently is 1/12 (~.05m) of the wavelength (~.60m) corresponding to the highest operating frequency (~500 MHz) of the GPR system in use. Flying a helicopter with a speed of 10 miles/hour and taking radar measurements every 5 milliseconds results in a rate of 200 Hz (200 Hz=1/0.005 sec) with a displacement of the airborne platform 0.022m on the ground. However, with an accuracy of 0.05m the maximum rate that can be used is 88.88 Hz (88.88 Hz=200 Hz x 0.022m/0.05m) which is easy to obtain with an INS system.

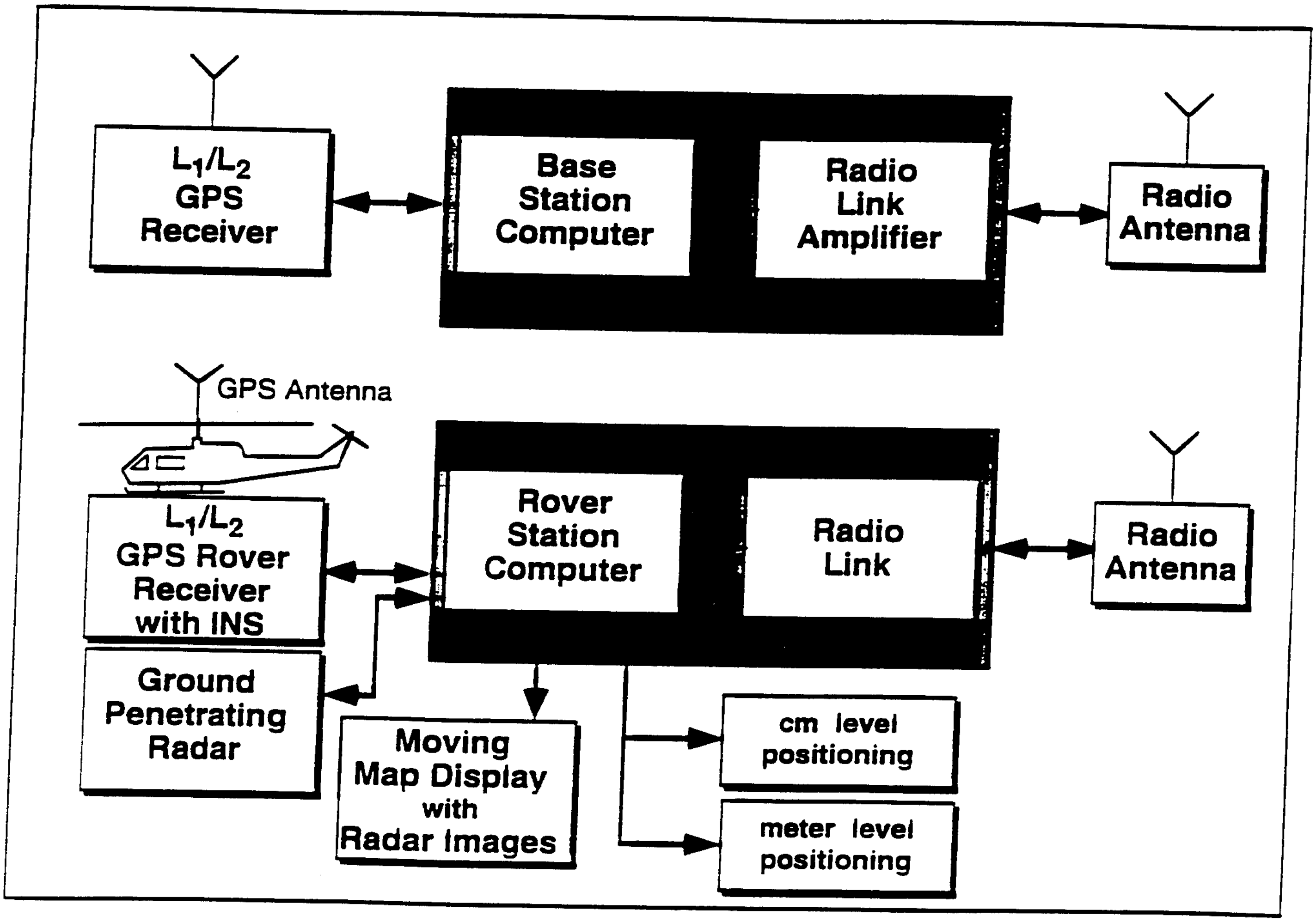

Figure 11 - Airborne Based Real-Time cm-level GPS Positioning System

Flying along a predefined survey line with a helicopter and the GPS antenna properly positioned, the GPS satellite signals will not be obstructed, assuming that electromagnetic interference from the GPR system or other sources will not cause any disruption of the GPS signal reception. Under these conditions the basic role of the INS system for the airborne platform will be to provide the higher position rates necessary to focus the GPR phase measurements. Without any obstruction and with GPS update rates of 1-2 Hz, the low cost LN-200 IMU is capable of providing the high positioning rates and the accuracy required for the focusing of the radar phase measurements.

Described below are the results of the GPS/GPR interference experiments at Jefferson Proving Ground in Madison, Indiana. From these results it is evident that a critical issue for the airborne platform is the location of the GPS antenna relative to the GPR antenna. The antenna for the airborne platform should be located on a place which minimizes interference between GPS and GPR as well as between GPS and other sources of electromagnetic radiation, and where the GPS satellite signals are not obstructed. One possible position of the antenna is to locate it above the main rotors. This position provides the most stable position as far as the airborne induced motion/vibration of the antenna itself is concerned. The following voice communication radio frequencies have harmonics in the main commercial GPS band of 1.57542 GHz are known to cause interference, and should be avoided: 121.050, 121.175, 121.2, 131.275, and 131.3 MHz.

The mounting of the antenna above the main rotor will be an expensive undertaking. The equipment mounted above the main rotor on attack helicopters can provide an approach to mounting as well as an estimate of the cost. Any other location which minimizes interference with the GPR antenna and allows tracking of all of the visible satellites will be a good location since the orientation provided by the INS will allow the transformation between the GPS and the GPR antenna phase centers. It is recommended to study the helicopter's electromagnetic interference to find a location for the GPS antenna, other than above the main rotor, which can satisfactorily receive both L1 and L2 signals. An alternate location should result in a less expensive installation.

As mentioned in the previous section, changes of the boundary atmospheric layer may reduce significantly the effects of the tropospheric models, making it very difficult or even impossible to perform high accuracy GPS positioning of the airborne platform. It is recommended to conduct experiments and establish the weather conditions that will allow high accuracy positioning of the airborne platform.

The IMU LN-200 has been tested for a variety of airborne environments for shock and vibration. Its operational temperature range is very wide and, therefore, it is not anticipated to have any operational problems coming from shock, vibration, and temperature changes. As for the GPS receivers, several airborne experiments using Trimble SSE or Turbo-Rogue receivers have been conducted. The ability to track the GPS satellites signals without any problems arising from shock, vibration or temperature changes, as long as the receiver was mounted rigidly inside the aircraft.

Interference between the GPR and GPS at Jefferson Proving Ground, Madison, Indiana, Sep 94

Differential GPS data was collected at a 1 Hz rate, as the vehicle on which the GPR was mounted was moving at approximately 0.27 feet/second. This data was processed using CFM GPS software to determine the vehicle's motion. The requirement is for ~0.07m positioning of the GPR in quasi real-time. The data discussed here is for the last 3.5 hour period on September 29, 1994.

The GPS satellites transmit signals at two frequencies, L1 and L2. Very accurate (cm-level) differential positioning can be achieved with only a few epochs of data using double difference widelane observables (L1-L2) derived from the L1 and L2 carrier phase observations for epochs when 4 or more satellites are available. The GPS receiver tracks the L1 signal more easily than the lower power L2 signal. If only L1 data is available, it is more difficult and takes longer (5 to 15 minutes) to determine the carrier phase ambiguities required for very accurate differential processing.

Figure 12 shows the motion of the satellites during the time of the experiment. The concentric circles represent the constant elevations, 0, 30, 60 and 90 degrees, and the azimuth is indicated circularly about the center of the graph. Only satellites with an elevation >5 degrees are indicated on this graph as those with elevations <5 degrees are excluded from the processing. The signals from low elevation satellites have relatively large errors as the signals travel longer distances through the troposphere and ionosphere. From figure 12 it can be seen that, at any time during the experiment, 6 to 8 satellites have elevations >30 degrees. This number of satellites is sufficient to achieve high accuracy (cm-level) differential GPS positioning. The quality of the GPS data collected during this experiment was unexpectedly poor. For a large number of the epochs throughout the duration of the experiment the L2 data and, in many cases, even the L1 data is missing. For many epochs, even though 6-8 satellites are available, less than 4 have L2 data and the accurate widelane processing cannot be performed. The data was processed on the basis of the L1 data, as described below.

Date: 1994/ 9/20

Location: Jefferson Proving Ground

Lat: 38:52:46.30 N   Lon: 85:22:33.00 W

Time Zone: Greenwich Std Time

Local Time - GMT = -0.00   Mask: .05 (deg)

>>> Satellite Sky Plot <<<

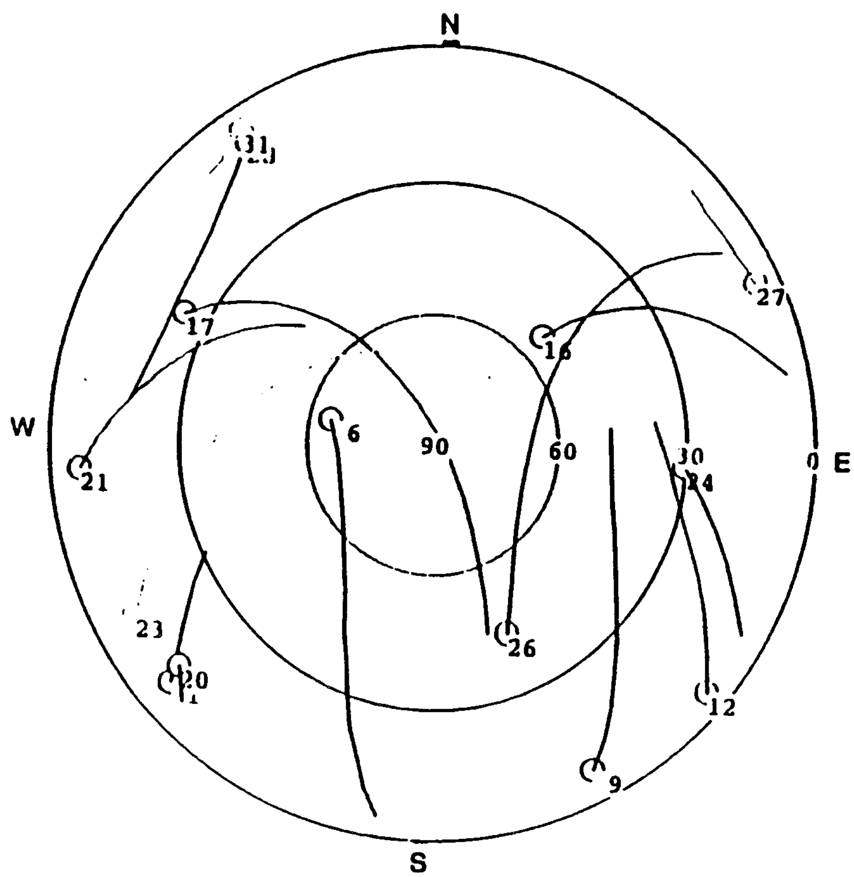

Figure 12 - GPS Satellite Trajectories

Figures 13 and 14 show the variation in the Position Dilution of Precision (PDOP) during the time of the experiment. The PDOP relates to the geometry of the satellites and varies in a regular fashion as this geometry changes. Figure 13 shows the expected PDOP calculated from the satellite orbits. Figure 14 shows the PDOP calculated from the satellites used in the processing, i.e., those satellites for which L1 data is available. The spikes in figure 14 occur when satellites are missing L1 data and the geometry of the satellites used in the processing has been altered. The spikes in the PDOP correspond to sudden accuracy degradation of the estimated velocities and positions as is seen by comparing figure 14 with figures 15, 16, and 17.

Figures 15, 16, and 17 show the change in position (velocity) between consecutive epochs for the east, north and up directions. For a large number of epochs the velocities appear as pairs of clipped vertical lines in the plots. At these times the geometry is either very poor or L1 data is available for less than 4 satellites, in which case velocities are not computed.

During the experiments the vehicle was remotely controlled, moving with a uniform speed of 0.27 feet/second in approximately the north-south direction. Comparing the velocities in figures 15, 16 and 17 with the PDOP in figure 14, it is evident that the velocities are incorrect by a large factor when there is a spike in the PDOP. So, low accuracy estimates of velocity are removed by rejecting velocities for which the PDOP is >2.5. The velocity for these epochs and for the epochs with less than four satellites being tracked have been estimated through linear interpolation. The results of the interpolation are shown in figures 18, 19, and 20. In these plots, the velocity measurements are much less noisy.

It is evident from these figures that even the cut-off PDOP value of 2.5 did not eliminate the non-uniform behavior of the estimated velocities. This is the result of the discontinuities in satellite tracking caused by the operation of the radar. These discontinuities will introduce systematic errors in the estimation of the position through the integration of the velocities. Although this method is very sensitive to the accumulation of systematic errors, it was used to estimate the positions because this is the only method that can produce accurate positioning with so many interruptions of the GPS satellite tracking.

The corresponding distances covered by the vehicle in the east, north and up directions, derived by integrating the velocities in the corresponding directions, were plotted in figures 21, 22, and 23. These show the general motion of the vehicle from its initial stationary position. The time at which the motion starts can be seen as the time at which the distance changes and at which

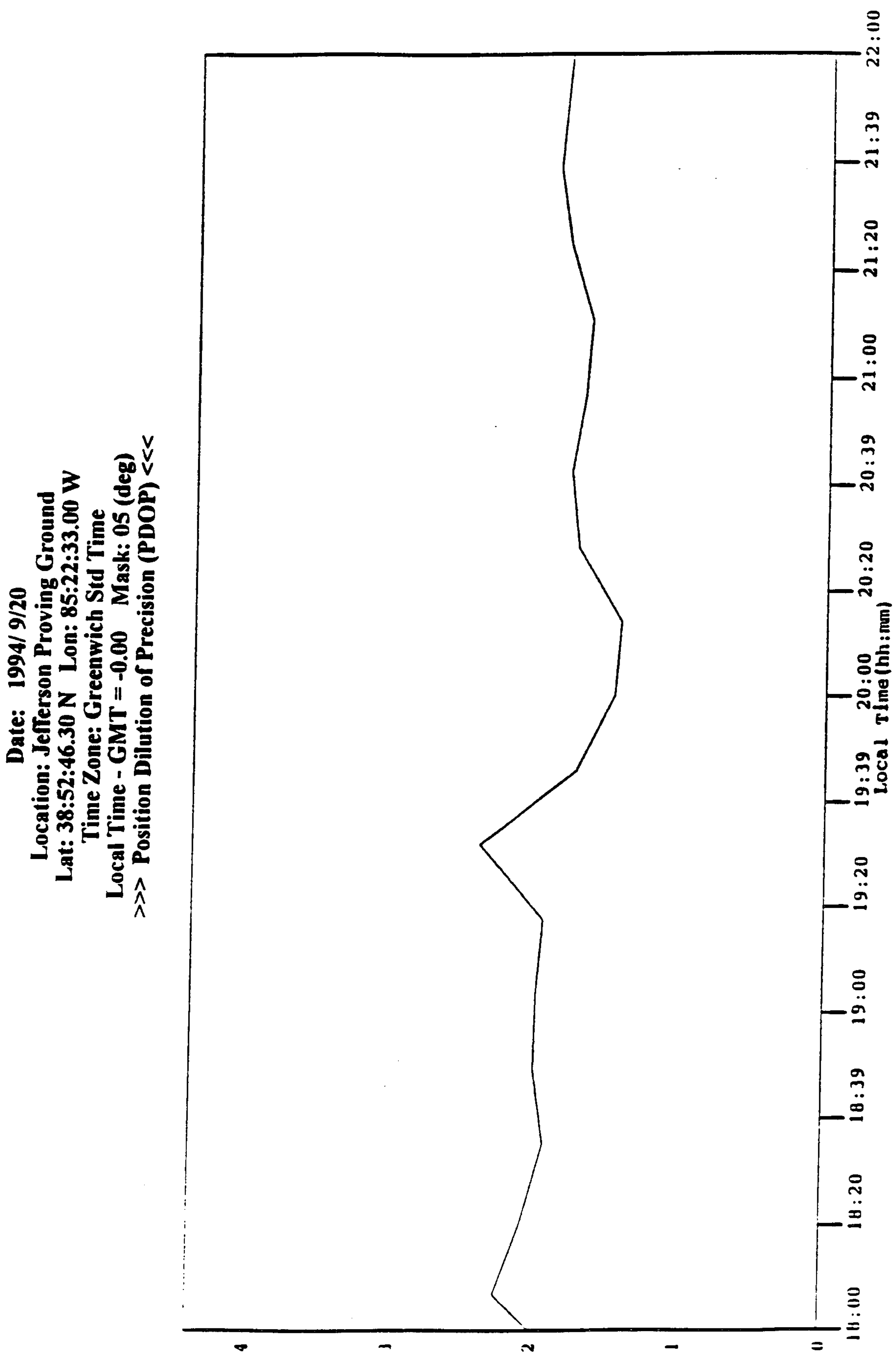

Figure 13 - PDOP for GPS Satellites

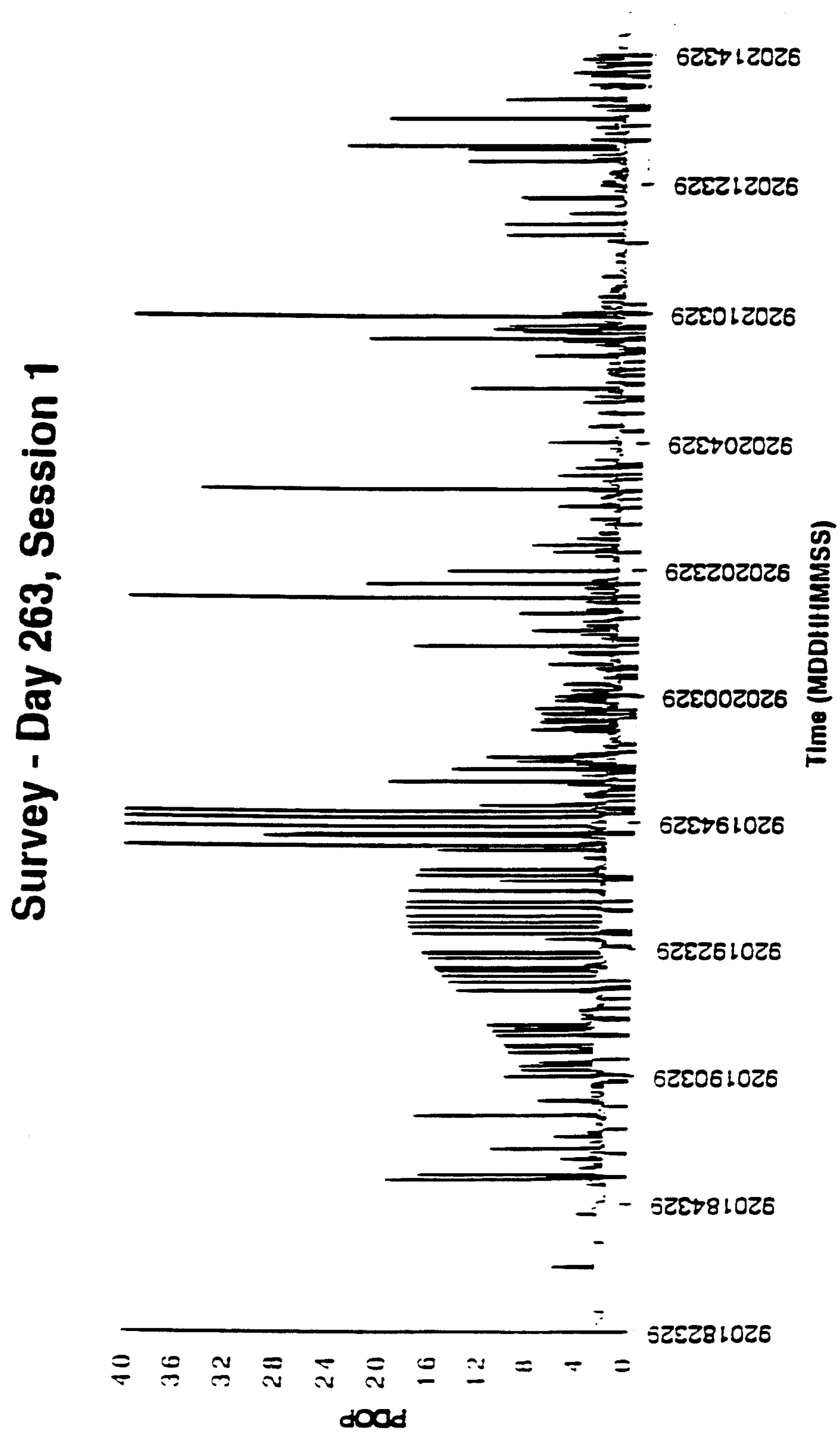

Figure 14 - PDOP for GPS Satellites with L1 Data

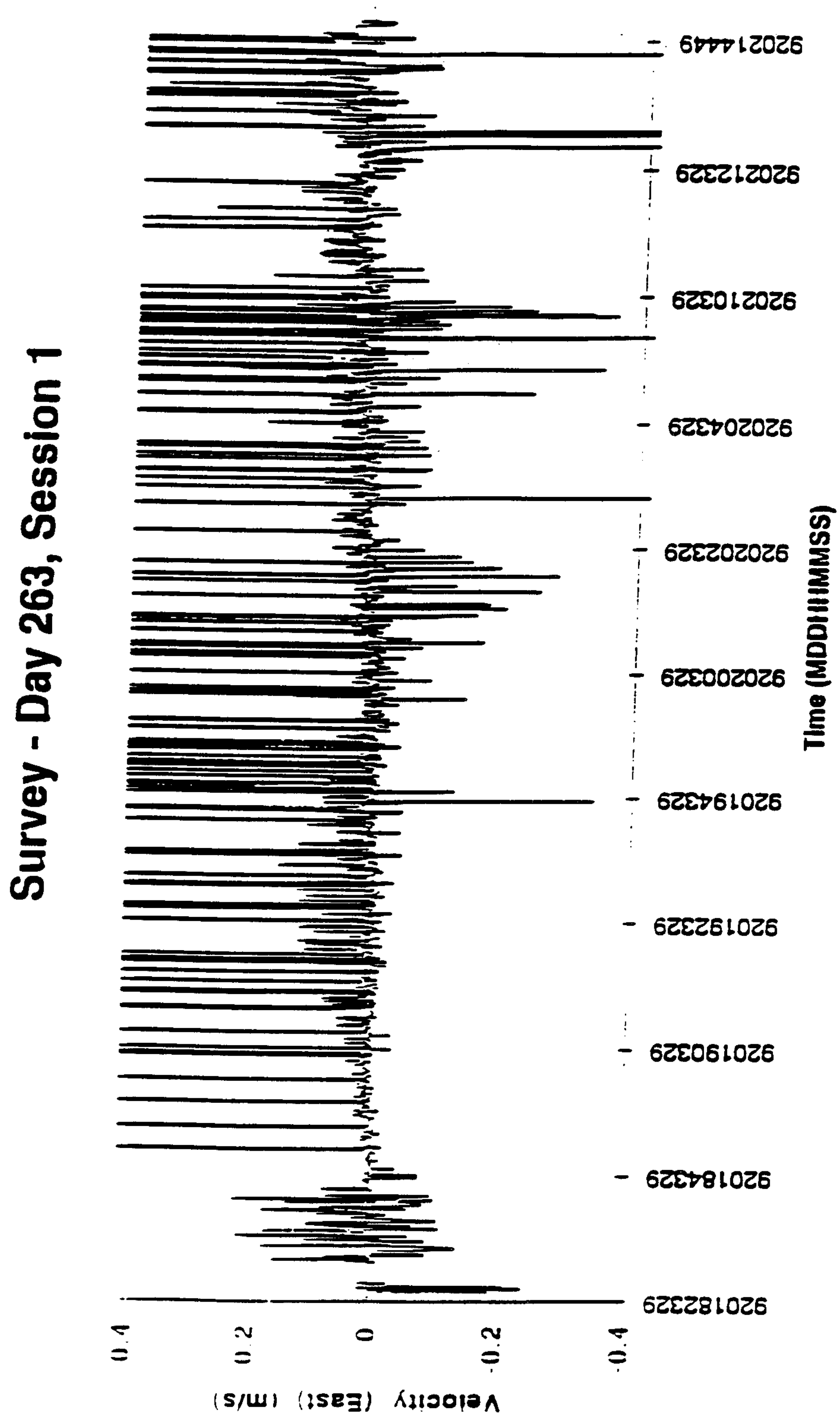

Figure 15 - Velocity (East)

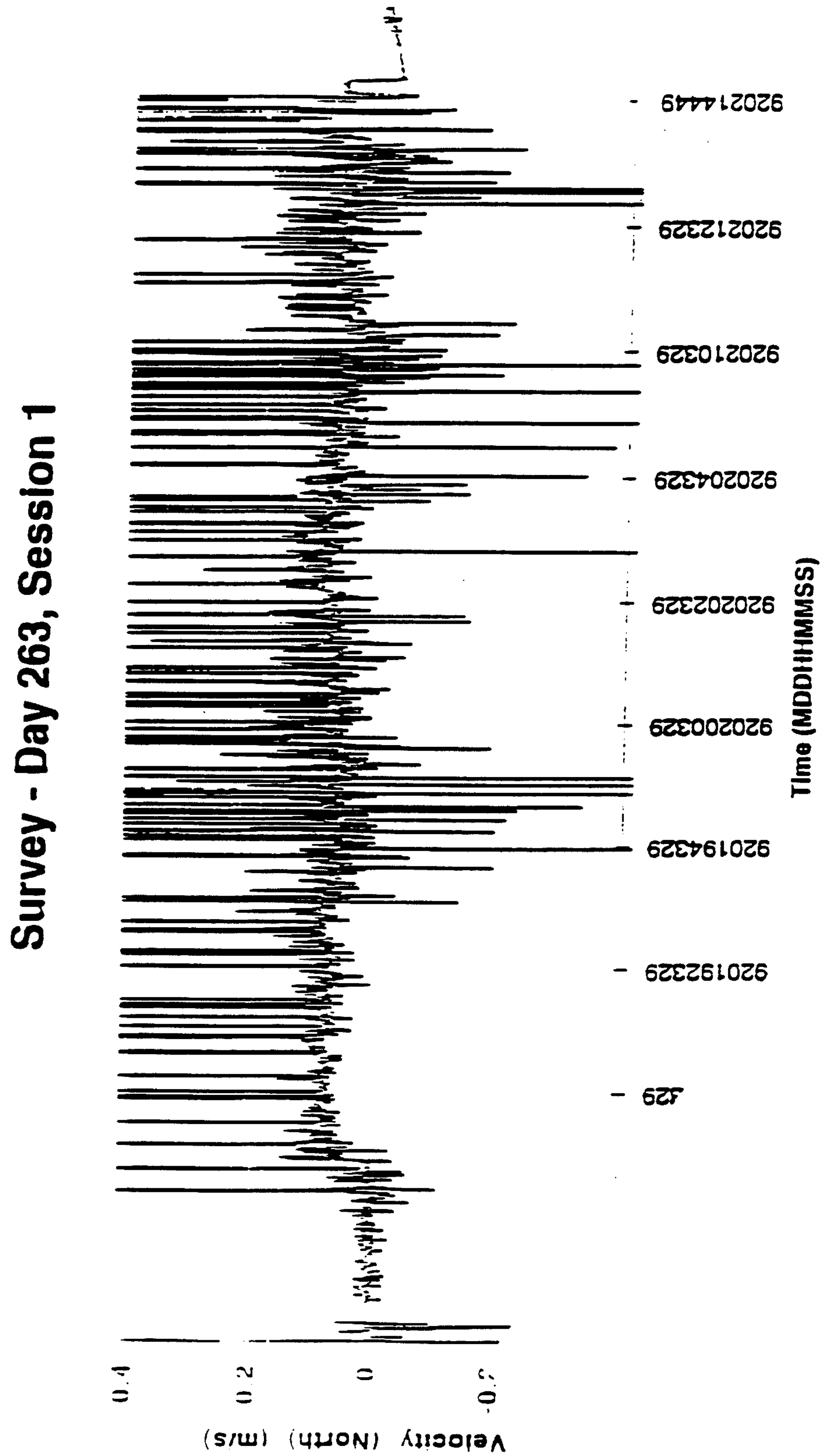

Figure 16 - Velocity (North)

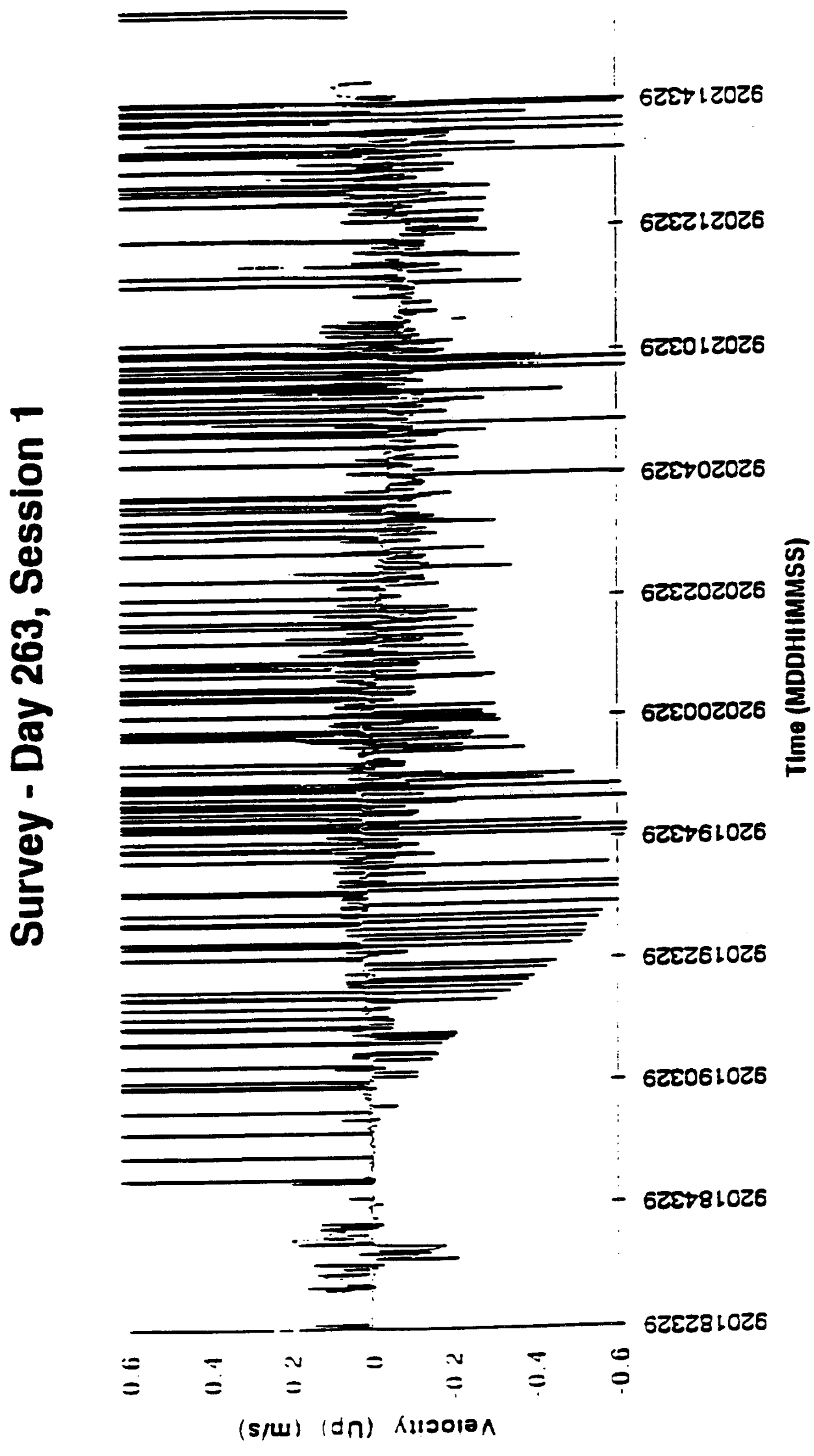

Figure 17 - Velocity (Up)

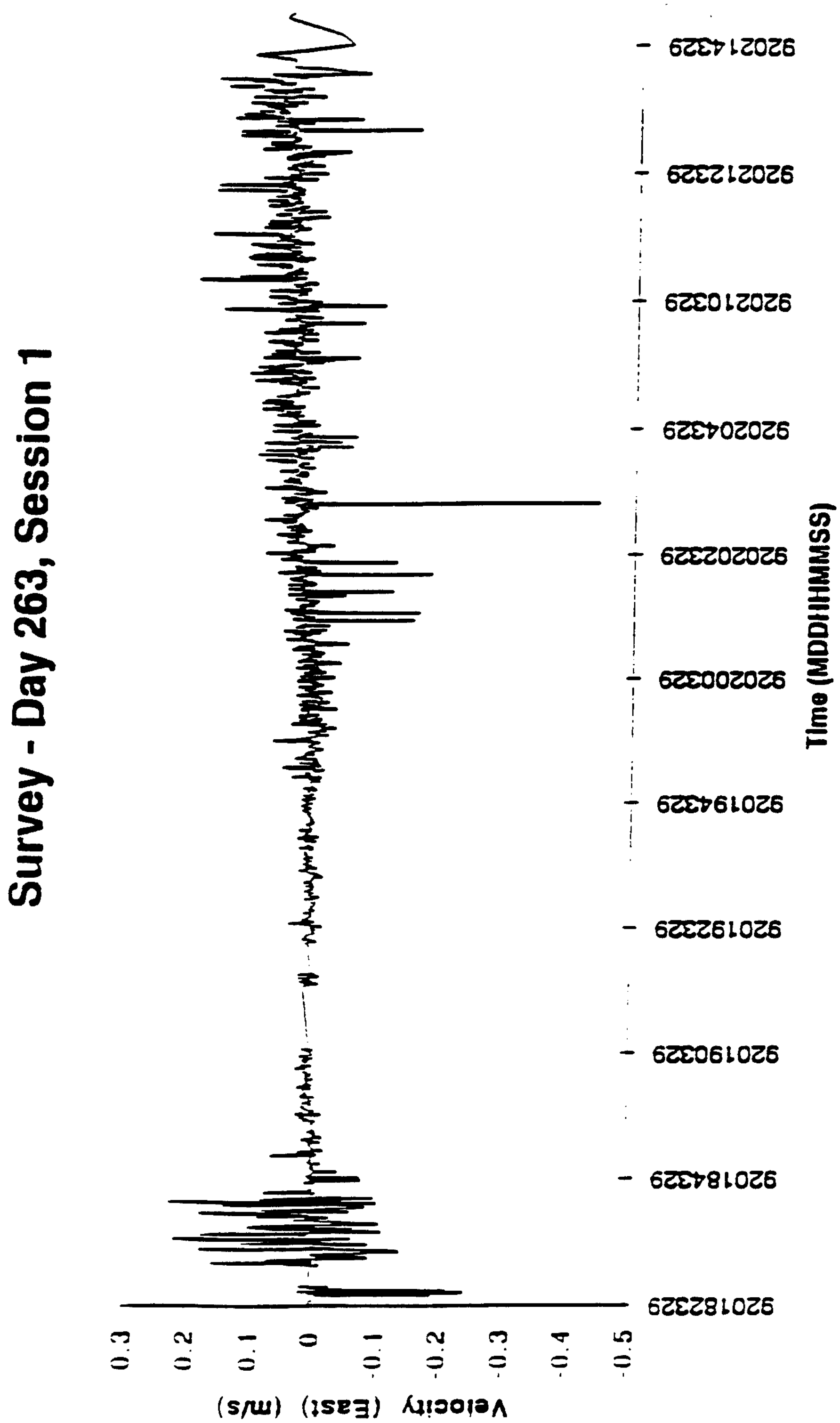

Figure 18 - Velocity (East) - Interpolated

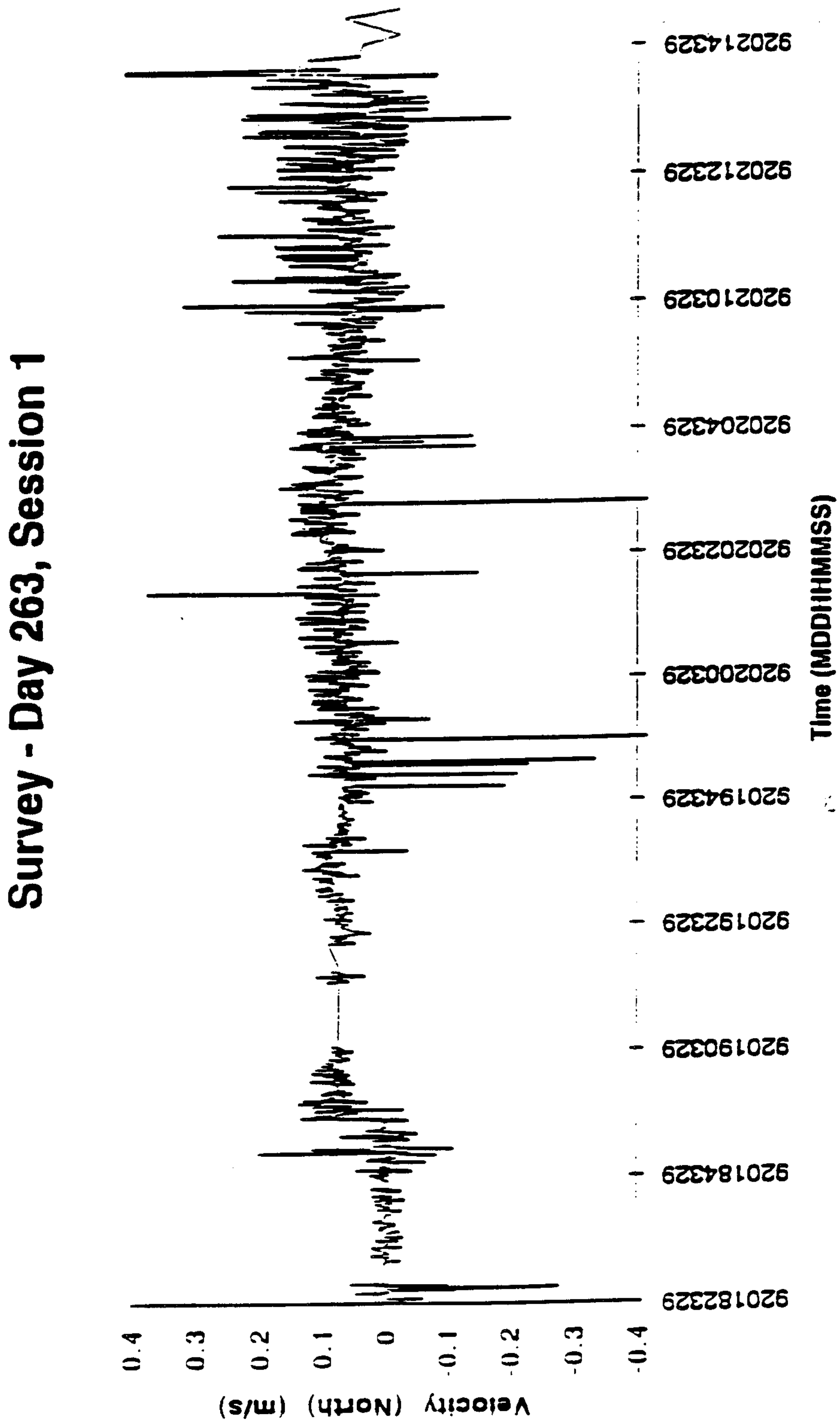

Figure 19 - Velocity (North) - Interpolated

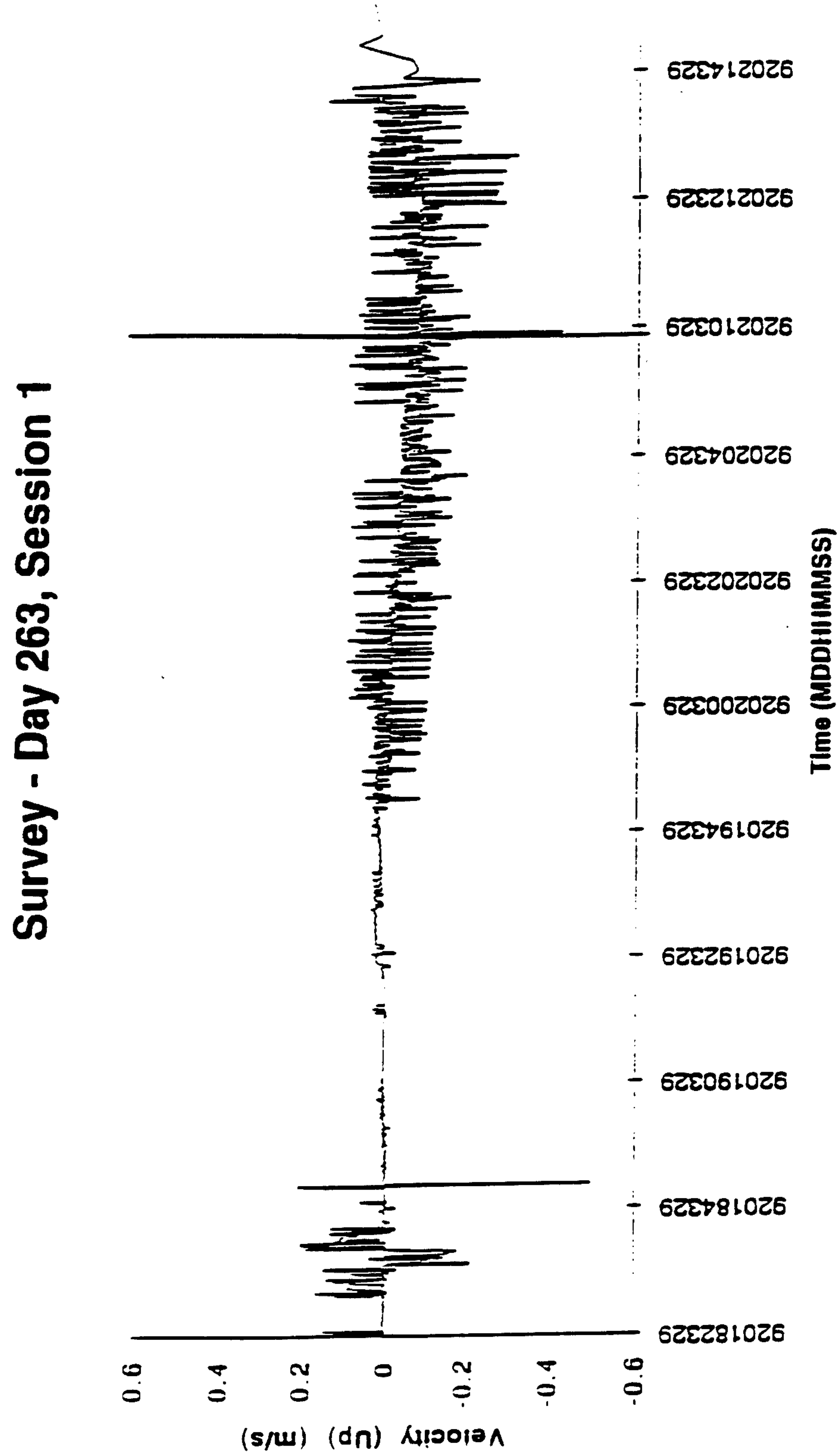

Figure 20 - Velocity (Up) - Interpolated

the velocity in the north direction (figure 19) changes. The interruption of the L1 signal is caused by interference with the signal from the GPR. Interference between GPS and GPR occurs when the GPR is transmitting in the neighborhood (+/-10 MHz) of its third harmonics corresponding to the L1 and L2 GPS frequencies. This interference is dependent on the GPR antenna pattern in relation to the GPS signal and can interfere with signals from high elevation satellites, for which the GPS data should otherwise be of good quality. The GPR was transmitting in the east-west direction and, examining the GPS data from the receiver mounted with the GPR data, satellites 16 and 17 moving from west to east (see figure 12) lose their L1 and L2 data very often. In fact, over the duration of the experiment none of the satellites were tracked continuously.

The plots in figures 18 through 23 show that the velocity and the corresponding distance can be determined despite the noise in the data. However, due to systematic errors introduced from the sudden changes of PDOP, this method of integrating the estimated velocities is not adequate to provide high accuracy results. It is recommended therefore, that for high accuracy positioning, the airborne GPR be equipped with filters to eliminate the interfering frequencies. It is also recommended to perform similar GPS/GPR interference experiments for the ground and man-portable platforms.

5.6.2 Conceptual Design of the Ground Vehicular Navigation System

The ground GPS navigation system is very similar to the airborne system. A block diagram of the real-time cm-level GPS/INS positioning system is shown in figure 24. This system consists of two units; the base and the rover units. The base unit consists of one computer, one dual-frequency GPS receiver, one radio receiver/transmitter, and a power amplifier, all of which are enclosed inside a waterproof enclosure for continuous operation in outdoor, exposed environments. The power amplifier is used to operate the system over distances of 20 miles. Without an amplifier, the system can operate over distances of 5 to 10 miles. For most of the UXO sites, the operating distance is less than 10 miles, and therefore, a power amplifier will not be needed for the base unit.

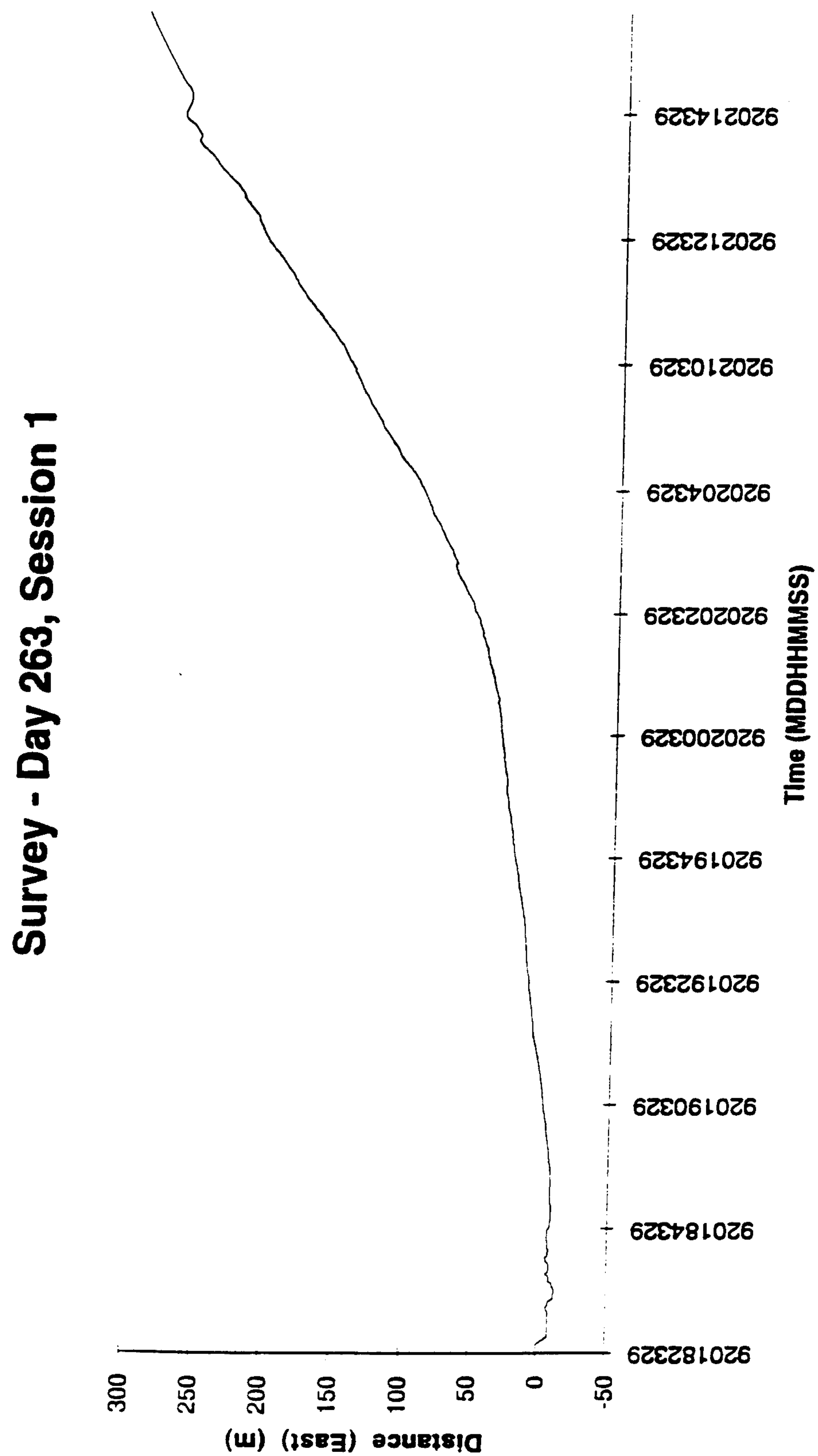

Figure 21 - Distance (East)

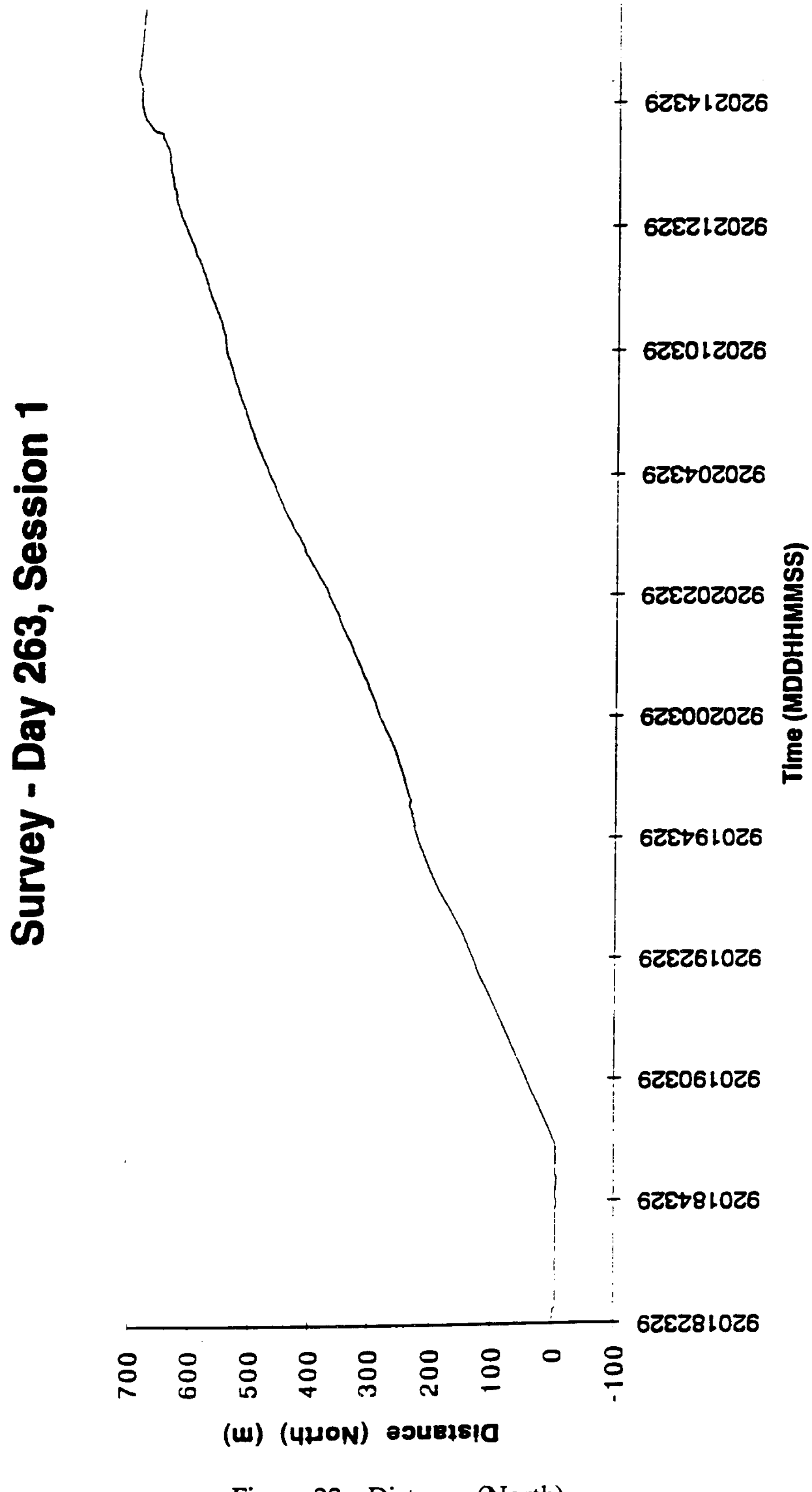

Figure 22 - Distance (North)

Figure 23 - Distance (Up)

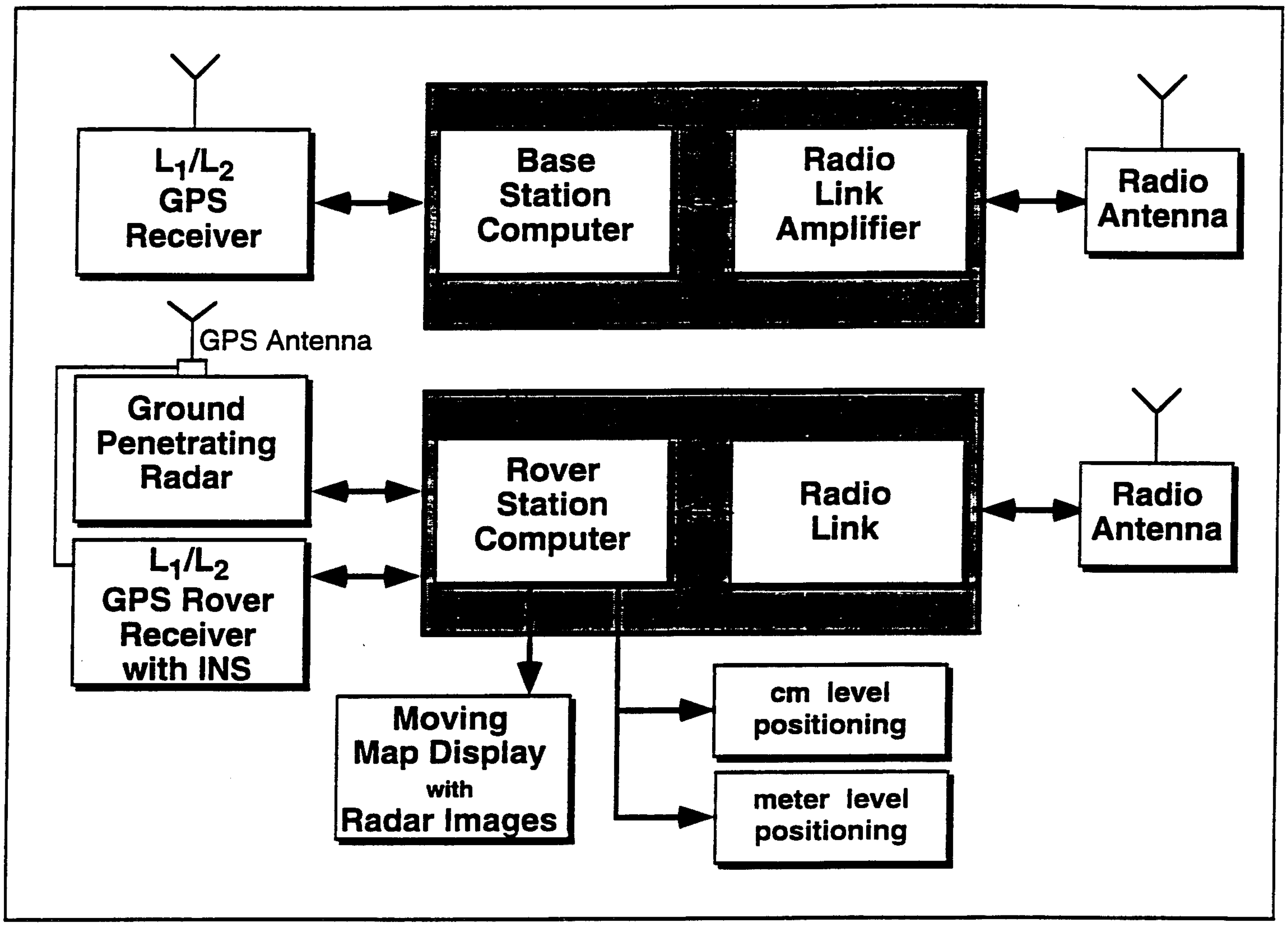

Figure 24 - Ground Based Real-Time cm-level GPS Positioning System

The rover unit consists of one computer, one dual-frequency GPS receiver integrated with an IMU and a radio receiver. The base station provides the differential GPS observations for real-time and post-processing cm-level positioning. The radio transmitter of the base unit transmits the differential observations to the rover unit for real-time cm-level GPS positioning. The real-time cm-level positioning is used at the Rover Station (ground platform; Subsurface Ordnance Characterization System) to focus the GPR phases in near real-time for the calibration of the GPR parameters.

The required accuracy to focus the GPR data coherently is 1/12 of the wavelength corresponding to the highest frequency. With the highest frequency of 500 MHz (~0.60m), the required positioning accuracy for focusing the GPR data is 0.05m (1/12 x 0.60m). Assuming that the ground-vehicle platform moves with a speed of 5 miles/hour and that the GPR makes measurements every 5 milliseconds (200 Hz), the distance on the ground between subsequent GPR measurements is 0.01111m. Since the required accuracy is only 0.05m, the GPR measurements should be averaged in time so that the time interval between subsequent radar measurements corresponds to a displacement of 0.05m on the ground. The time interval required to move 0.05m with a speed of 5 miles/hour is 22.5 milliseconds corresponding to a rate of 44.44 Hz. Therefore, the highest rate that can be used is 44.44 Hz. With higher navigation accuracies, less averaging will be required for the radar measurements. Less averaging of the raw radar measurements may potentially allow more efficient focusing, because the required averaging will be determined and it will take place at the digital image processing stage when the buried objects are identified.

Interference between GPS and GPR for the ground platform is possible and can be detrimental to high accuracy navigation. The experiment presented in section 5.6.1 were performed using a frequency domain (step-chirped) system with high transmitting power (~1 Watt). The ground-vehicle GPR will be a time-domain system with an output power substantially lower than the output power of the frequency domain airborne GPR system. With lower power, it is possible that the ground GPR system will not interfere with the GPS satellite signals. It is recommended, therefore, to conduct interference experiments between GPS and GPR using the exact GPR system that will be used for the ground platform. In the ground platform environment, it is very likely that for certain periods of time, the GPS signals will be obstructed by high trees with thick foliage. For proper focusing of the GPR phase data, it is important to navigate with high accuracy (~.05m) during these periods of time. This can only be achieved by integrating GPS with a high accuracy IMU able to maintain cm-level accuracy for several minutes. From figures 9 and 10 it is evident that the LN-100 IMU is able to deliver .05m - 0.10m accuracy in smoothing mode for 3 to 5 minutes without any GPS updates. As seen in figure 10, the accuracy of the IMU is much worse in free-inertial mode than the accuracy obtained in smoothing mode. For the focusing of the GPR data the navigation solution will be based on the smoothing mode because the position of the ground-platform is needed either in near real time (~1-2 minutes delay) for the focusing and calibration of the GPR or in post-processing for the final focusing of the GPR phase measurements. If the GPS signals are obstructed for longer periods, then the ground platform should come to a complete stop and perform a ZUP.

For the ground platform, the integration of the GPS with an IMU should be performed at the measurement level (tight), rather than at the position level (loose). Integrating GPS with IMU at the measurement level makes it possible to correct the IMU errors using measurements even during periods when less than four satellites are visible. Integrating GPS with an IMU at the position level (loose integration) assumes that GPS positions are available, which requires measurements from at least four satellites. In the ground platform environment, however, there will be many times when less than four satellites will be visible due to obstructions. During these times, it will be necessary to correct the INS, which necessitates integration of GPS with the IMU at the measurement level. With less than 4 satellites visible, ZUPs will be required when the time interval between the GPS updates is longer than 5 minutes. This time interval will depend on the strength of the GPS satellite measurements.

Another important issue is the type and the location of GPS antenna on the ground platform. The Simultaneous Data Collection and Processing System (SIDCAPS) on the ground platform will be equipped with an array of sensors, including the GPR and magnetometers positioned on a trailer that is towed around the designated site. The optimum position of the GPS antenna and the INS is on the sensor trailer and not on the tow vehicle. The GPS antenna should be positioned anywhere on the trailer above any trailer obstructions, where the GPR interference is minimum. The GPS antenna should be of geodetic type (i.e., equipped with a ground plane) to minimize the effect of multipath (i.e., reflected satellite signals) originated at the sensor trailer or the tow vehicle. Having an IMU and the GPS antenna on the sensor trailer makes it possible to transfer the GPS antenna phase center to the GPR antenna phase center using the orientation parameters provided by the IMU. If the IMU and/or the GPS antenna are located on the tow vehicle, then additional sensors (i.e., linear or rotary sensors) must be provided to measure the relative orientation of the tow vehicle and the sensor trailer. This implementation will make the system more complicated and more expensive.

It is recommended that the GPR/GPS/IMU be developed as a separate unit that will provide the GPR/GPS/IMU data to the control computer located on the tow vehicle. The control computer will display the current position of the GPR antenna on a moving map display (section 6), and it will perform the near real-time focusing of the GPR phase data for calibration of the operational GPR parameters. The control computer will receive the base station differential GPS data, and it will combine the GPS data from both GPS receivers with the IMU data to compute high accuracy positions of the GPR antenna phase center.

Another alternative is to have a computer as part of the GPR/GPS/IMU system. This computer will receive the differential GPS data from the base station, and it will combine the GPS

data from base and rover GPS receivers with the IMU data to compute real-time high accuracy positions for the GPR antenna phase center. It will perform the near real-time focusing of the radar data and it will send the results to the tow vehicle control computer. The positions will be shown on a moving map display, and the near real-time focusing results will be displayed for the calibration of the GPR operational parameters. This kind of design is more modular, and it makes the GPR/GPS/IMU system independent of any sensor trailer or tow vehicle configuration.

The modeling of the tropospheric delay for the ground stations is very accurate, on the order of 0.01m - 0.02m, which is adequate for the 0.05m positioning required for GPR phase measurements. The temperature, shock and vibration range of the IMU and GPS instruments is very wide, and therefore, it is not anticipated to have any problems, especially when shock and vibration mounting is used.

5.6.3 Conceptual Design of the Man-Portable Navigation System

The functionality of the man-portable GPS/IMU navigation system is very similar to the ground navigation system. The basic difference is that the man-portable system should be portable. Therefore, all of its components, ranging from the GPR antenna to the IMU system, should be portable components. As described below, the low weight requirement of the man-portable system will place a limit on the accuracy of the employed IMU system.

A block diagram of the man-portable system is shown in figure 25. This system consists of two units: the base unit and the rover unit. The base unit is the same as that employed for the airborne and ground systems. It consists of one computer, one dual-frequency GPS receiver, one radio receiver/transmitter, and a power amplifier — all of which are encased within a waterproof enclosure for continuous operation in outdoor, exposed environments. The power amplifier is used to operate the system over distances of 20 miles. Without an amplifier, the system can operate over distances of 5 to 10 miles, which will be sufficient for most of the UXO sites where a man-portable system is required. The rover unit consists of a portable computer, one hand held GPS receiver integrated with an IMU and a radio receiver.

The man-portable GPR unit should be built to operate in rough areas where the ground system is not able to operate. For this reason, the man-portable unit is housed inside a golf cart as shown in figure 25. The impulse generator (i.e., time-domain GPR) and the batteries are housed in the lower module of the golf cart. The GPS receiver, the computer with the display showing the moving-map, and the results of the near real-time GPR focusing are housed in the upper part of the golf cart. The transmit-receive antenna pair consists of orthogonal, resistively loaded

dipoles. The IMU system is placed on the top of the GPR antenna, which is designed to slide on the ground (figure 25).

The LN-100 high-accuracy system, recommended for the ground platform, weighs 18.5 pounds, making it inappropriate for use in the man-portable platform. For this reason, the LN-200 IMU, which weighs only 1.54 pounds, is recommended for use. A full blown INS (LN-210) with an LN-200 IMU engine weighs 8.1 pounds. Therefore, it is recommended that for the man-portable system, the LN-200 IMU be tightly integrated with GPS, which will keep the weight of the GPS/IMU system much lower. The tight integration of the IMU with GPS will provide high accuracy navigation for longer periods of time with less than four satellites in view. The man-portable platform is very likely to track less than four satellites due to satellite signal obstructions caused by high trees with thick foliage. Furthermore, the IMU unit will provide the orientation parameters needed to transform the GPS phase center to the GPR phase center when the system is operating in rough terrain with high slope. The GPS antenna should be placed high enough so that the person operating the man-portable platform does not obstruct the GPS satellite signals.

It is evident from figure 9 that the LN-200 IMU unit can maintain an accuracy of 0.10m for about 1 minute. This period can be extended by several more minutes when less than 4 satellites are tracked and the GPS is tightly integrated with the IMU. However, if the positioning accuracy deteriorates to less than 0.15m, the man-portable platform should come to a complete stop and perform a ZUP. Employing an LN-100 IMU unit will provide longer periods between ZUPs, but it will make the system heavier and maybe non-portable. These factors should be taken into consideration when building a man-portable system.

As mentioned in the previous section, the required accuracy to focus the GPR measurements is 1/12 of the wavelength of the highest frequency, which is 0.05m, for a frequency of 500 MHz. If a man-portable platform moves with a speed of 1 mile/hour and the GPR measurements are recorded every 5 milliseconds (200Hz), then the distance between subsequent GPR measurements is 0.0022m. Since the required accuracy is 0.05m, it is recommended that the GPR measurements be averaged in time so that the time interval between subsequent GPR measurements corresponds to a displacement on the ground of 0.05m. This time interval for a platform moving with 1 mile/hour is 0.1125 seconds corresponding to 8.88(~9) Hz. Therefore, the highest GPR rate that can be used for a man-portable platform is 9 Hz.

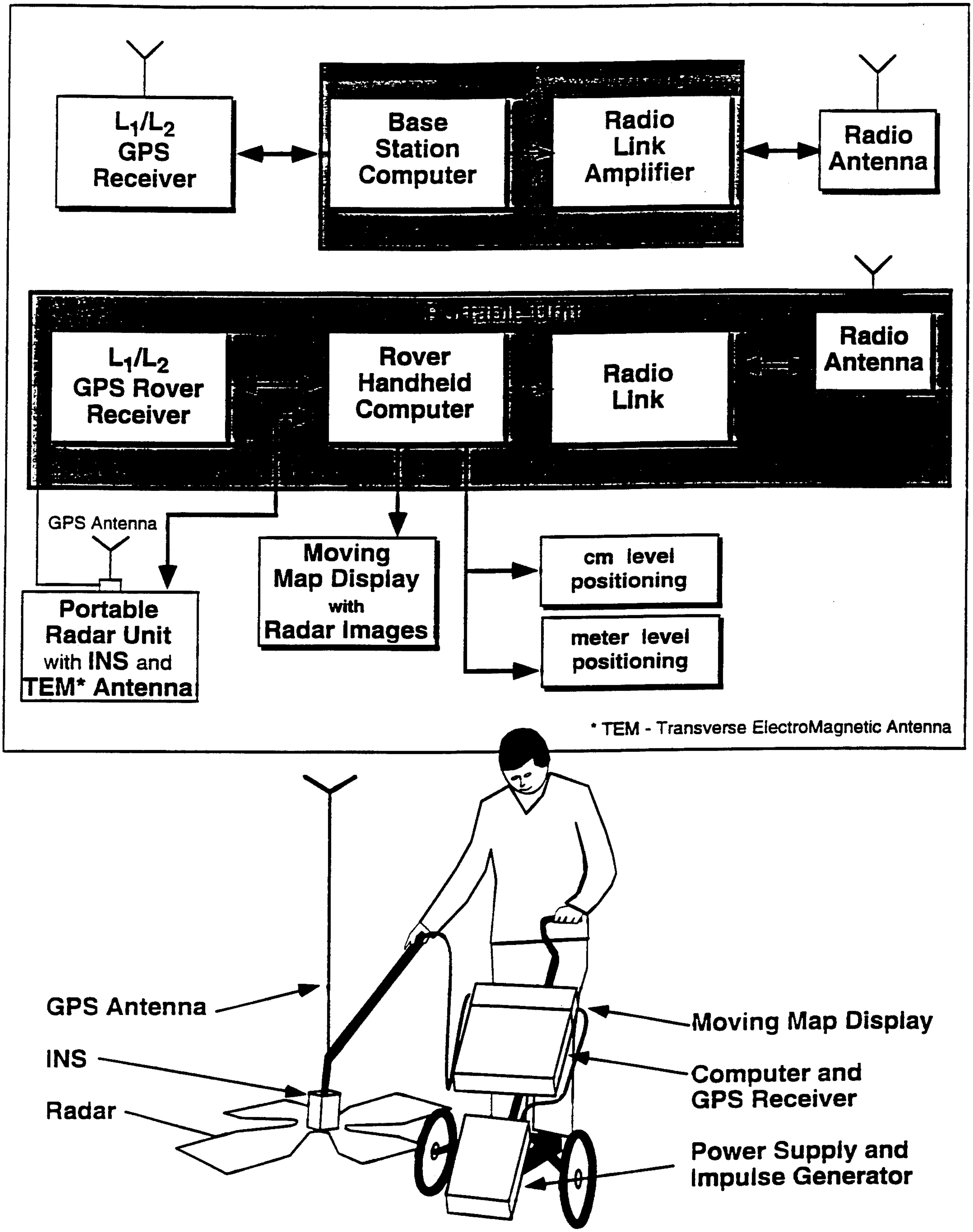

Figure 25 - Man-Portable Real-Time cm-level GPS Positioning System

Interference between GPS and GPR for the man-platform is possible, and can be detrimental to high accuracy navigation. The GPR system employed in the man-portable platform will be a time-domain GPR with an output power substantially lower than the output power of the frequency domain airborne system. Interference is possible and, therefore, it is recommended to conduct interference experiments between GPS and GPR using exactly the GPR system that will be employed in the man-portable platform.

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6.0 NAVIGATION DISPLAY

An integral part of each platform is a moving-map display showing in real-time the position of the moving platform overlaid on a moving map. This capability allows the operator of the multi-sensor platform to survey the areas of interest according to predetermined survey lines. The Center for Mapping has established the moving map display requirements, has performed an extensive search of all commercially available moving-map display modules, and has evaluated the advantages and disadvantages of these modules in meeting the system's requirements.

For the navigation of each platform it is important to follow predefined survey lines as closely as possible to ensure complete coverage of the surveyed area. The navigator must have access to accurate course information and corrections.

One role of the GPS is to provide course corrections: GPS gives the actual position, which is compared with the predefined desired course to determine the required course correction.

A moving map display will provide current course requirements and course correction in a usable form to the navigator. Moving map displays with GPS interfaces have been shown to be feasible and useful tools in current commercial products for aircraft navigation (e.g., LapMap) and ground based navigation (e.g., MapInfo).

6.1 Moving Map Display Requirements

The moving map software must be able to:

- Import maps (TBD format) at a variety of scales - if a map is not available, the software will show position relative to the user overlay.
- Display multiple maps (at least two) for coarse and fine detail.
- Provide online access to multiple maps, zoom and panning capability.
- Allow map manipulation, e.g., capability to alter map orientation, provide motion of position overlay rather than map.
- Import and display the predefined course as lines on the displayed map.
- Display additional data (overlaid text) to aid navigation. It is recommended that this data be updated when appropriate; e.g., with current position.
- Import GPS and INS position data via a database. GPS and INS data must be

accessible to other GPS software. If a direct link is used, the map software must not restrict accessibility.

- Interface with the selected GPS and INS.
- Provide coordinate transformations between map and GPS positions.
- Display current GPS position.
- Display actual course (from historical GPS/INS data).

Hardware and software interfaces to the moving map display include:

- Use of a portable or ruggedized system and use of special input devices.
- Implementation as a workstation vs PC-based system.
- Graphical User Interface (GUI) (XWindows vs MS Windows), software language interface (C vs proprietary interface such as a script language).

Other requirements that affect the moving map display include:

- Availability of maps of the surveyed area that would make the display more readable; putting the overlay in context with external features.
- The ability to navigate to the required accuracy and aspects of course correction will affect the usefulness of the system.
- The update rate of the map display must be sufficient for navigation at the expected vehicle speeds.

6.2 Approaches/Characteristics

The following is a survey of software products that appear to support the required capabilities. In particular, these products allow the user to import maps and overlay predefined survey lines.

Much of the commercial moving map display software has been developed for end-users in nautical and airborne navigation and is too specialized for these applications. The moving map display software products, which appear to support the required capabilities, have clearly been designed to support selected application markets with very different requirements than those of this project.

The following four software products have the capabilities to satisfy the requirements for the UXO, detection, identification, and remediation program:

- MapInfo
- XMap
- Geographic View/Tracker
- Field Notes

All of the above products allow the users to import maps in a variety of formats, to annotate, and associate points on the map with data from popular database products. All of these products provide zooming of the main map display and simultaneous display of text windows. The developer's software license may be required to overlay predefined course lines and to incorporate other requirements not available in the basic moving map display software products.

Direct GPS interfaces or serial port interfaces are optionally available for all of the above products. The direct GPS interfaces support many common GPS receivers, provide a summary of GPS information, and display the current GPS position on the moving map display.

Table 6 describes the basic capabilities and the pricing of the moving map software products mentioned above:

Table 6
Comparison of Moving Map Software Products

	Xmap - DeLorme Mapping	Map Info - Mapinfo Corp	Geographic View/Tracker - Blue Marble Geographics	FieldNotes - PenMetrics
Multiple Map Display	√	√	√	√
User overlay of predefined course lines	√	√	√	√
Platforms	UNIX, MS Windows	UNIX PC (DOS, MS Windows) Mac	UNIX PC (DOS, MS Windows) Mac	MS Windows
Direct GPS Interface	PC only	√	√	√

	Xmap - DeLorme Mapping	Map Info - Mapinfo Corp	Geographic View/Tracker - Blue Marble Geographics	FieldNotes - PenMetrics
Cost of Basic Products	$5,000 and up	≈ $1,500	≈ $1,000	≈ $1,000
Additional Costs	Developers software *x* $25,000 significant royalties on developed products	Developers software (script language) $800 and up	Developers software $5,000 and up	Developers software $2,000-$3,000

The least expensive (~$1,000 - $5,000) of the surveyed software products are designed primarily as end-user products for a variety of mass markets. Some products can be customized to a limited extent using simple proprietary script languages.

6.3 Recommendation

The moving map display product, required to support the UXO detection, identification, and remediation program, is not a typical application for the off-the-shelf commercial products. To minimize the risk and the customization costs, it is recommended to use an existing product that can be modified using the developer's software to meet the requirements of the UXO project.

With the above considerations in mind, the Center For Mapping has developed a relationship with Blue Marble GeoGraphics, a company with products with which CFM is already familiar. This will ensure the success of the moving map display product in support of the UXO detection, identification, and remediation technology.

7.0 CONCLUSIONS AND RECOMMENDATIONS

7.1 Hardware/Software

Before proceeding with the Phase II development of the ground vehicular, man-portable and airborne platforms, several system integration issues should be addressed and a decision made on a common system by all parties involved in the development of the multisensor platforms. These issues include hardware platforms (e.g., PCS, workstations), software development language(s) (e.g., FORTRAN, ANSI C, C++), software communication (e.g., multiple CPUs, single CPU with multitasking and Interprocess Communication (IPC) capabilities), data interfaces to external hardware (e.g., ISA, EISA, VME bus), and GUI platforms (e.g., MS Windows, Win32, Xwindows). Appendix C presents a list of recommended hardware and software for use in UXO remediation efforts.

7.2 Electromagnetic Interference

Interference between GPS and GPR occurs when the GPR is transmitting in the neighborhood (±10MHz) of its third harmonics corresponding to the L1 and L2 GPS frequencies. This interference results in losses of lock to the L2 signal for the majority of the satellites. Missing the L2 data for most of the satellites will be detrimental to high accuracy positioning both in real-time and in post-processing. To solve this interference problem, it is recommended that the GPR be equipped with filters that will eliminate completely the transmission of the interfering frequencies.

7.3 GPS Configuration

For the GPS, it is recommended that either Trimble or Turbo-Rogue receivers, equipped with geodetic GPS antennas be used for the base stations. For the airborne platform, an airplane antenna should be employed.

7.4 Integrated GPS/INS

A combination of GPS with an INS or IMU will provide positioning information that covers the requirements of the GPR. For the ground-vehicle platform, a high accuracy IMU system is needed to maintain the required accuracies during the periods when the GPS satellite signals are not available due to obstructions. For the man-portable platform, a high accuracy IMU (LN100) would be preferable. However, the high accuracy IMU units tend to weigh more and, therefore, are not suitable for a man-portable system. For this reason, it is recommended that a low-cost low-weight IMU unit be used for the man-portable system. The

lower accuracy IMU will require more frequent ZUPs when the GPS signals are not available. For an airborne system, the expected periods of GPS outages will be in the order of a few seconds. Therefore a low-cost, low-accuracy IMU (LN200) will provide the .07m accuracy requirements in both quasi real-time and in post-processing.

7.5 Map Display

The moving map display product, Geographic View/Tracker from Blue Marble GeoGraphics, is recommended to support the UXO detection, identification, and remediation program. It is an existing product, familiar to CFM, that can be modified using the developer's software to meet the requirements of the UXO project.

APPENDIX A

MATHEMATICAL MODEL FOR GPS ON-THE-FLY AMBIGUITY RESOLUTION

In the static environment, the changing satellite geometry allows the separation and estimation of the carrier phase integer ambiguities from the constant station geometry. In the dynamic environment, however, both station and satellite geometries are changing simultaneously. As a result, the separation of the integer ambiguities from the station-satellite geometry is more difficult, especially within short periods of time. In this case, code phase positioning in combination with OTF ambiguity resolution is used to estimate the carrier phase ambiguities.

Several OTF ambiguity resolution techniques have been proposed in the past ranging from ambiguity function techniques to ambiguity reparametrization (Counselman and Gourevitch, 1981; Hatch, 1990; Mader, 1992; Lachapelle et. al., 1993; Landau, 1993; Remondi, 1993; Abidin, 1993; Dedes and Goad, 1994; and Teunissen, 1994).

For short baseline lengths, the effect of the ionosphere is very small and therefore it can be neglected. In this case, the three measurement model takes the form (Dedes and Goad 1994):

$$DD(R1) = DD(\rho) + DD(\varepsilon R1) \qquad (1)$$
$$\lambda 1 \times DD(\phi 1) = DD(\rho) + \lambda 1 \times DD(N1) + DD(\varepsilon\phi 1) \qquad (2)$$
$$\lambda 2 \times DD(\phi 2) = DD(\rho) + \lambda 2 \times DD(N2) + DD(\varepsilon\phi 2) \qquad (3)$$

where DD is the double difference operator (difference of GPS measurements from two stations and two satellites at the same observation time) and R_1, ϕ_1, and ϕ_2 are the pseudorange, carrier phase L1, and carrier phase L2 measurements: ρ is the pseudorange affected only by tropospheric effects; N1 and N2 are L1 and L2 carrier phase ambiguities (the number of complete wavelengths by which the receiver phase measurements are in error when satellite tracking starts); ε_{R1}, $\varepsilon\phi_1$, and $\varepsilon\phi_2$ represent the noise affecting the pseudorange and the L1, L2 carrier phase measurements. Filtering the data using equations (1) through (3) yields the widelane ambiguities:

$$wd = DD(N1) - DD(N2) \qquad (4)$$

which together with the geometry-free L1/L2 carrier phase combination:

$$DD(\phi 1) - (77/60) \times DD(\phi 2) = DD(N1) - (77/60) \times DD(N2) + DD(\varepsilon\phi 1) - DD(\varepsilon\phi 2) \qquad (5)$$

form the basis for the ambiguity resolution. Proper filtering of the left side of equation (5) will reduce the effects of noise and multipath, but it will still be affected by unmodeled systematic affects of residual ionosphere, troposphere and multipath. For short filtering times and in the presence of systematic errors, the equations are not really equations but inequalities of the form:

$$-dw_1 \leq wd - (DD(N1) - DD(N2)) \leq dw_1 \quad (6)$$

$$-d\phi_1 \leq DD(\phi_1) - (77/60) \times DD(\phi_2) - (DD(N1) - (77/60) \times DD(N2)) \leq d\phi_1 \quad (7)$$

The value of dw_1 depends on the accuracy of the pseudoranges, and the value of $d\phi_1$ depends on accuracy of the carrier phases. Consequently, the value of dw_1 is usually much larger than the value of $d\phi_1$.

The solution to the ambiguity problem is to find the set of all possible *DD(N1)* and *DD(N2)* pairs for all satellites satisfying inequalities (6) and (7) with the constraint that all these pairs correspond to the same position in space. To solve this problem, the values for dw_1 and $d\phi_1$ should be estimated, and a searching range for *DD(N1)* and *DD(N2)* needs to be established. The values dw_1 and $d\phi_1$ of depend on the elevation angle of the corresponding satellite, and they can be established from their accuracy estimates.

The searching range of *DD(N1)* and *DD(N2)* is established by solving equations (4) and (5) and using the fact that a 0.1 cycle error in the geometry-free carrier phase ambiguities introduces an error of .353 cycles in the estimation of *DD(N1)* or *DD(N2)*.

For long baseline ambiguity resolution, the three measurement filter should be replaced with the four measurement filter, the geometry-free L1/L2 carrier phase should be replaced with the iono-free L1/L2 combination, and the *DD(N1)* and *DD(N2)* searching range should be established from the values and the accuracy of the *DD(N1)* and *DD(N2)* filter estimates.

APPENDIX B

MATHEMATICAL MODEL FOR INERTIAL NAVIGATION

The equation of motion of a body in a non-rotating, freely falling coordinate frame, called the **i-frame**, is given by

$$\ddot{r}^i = a^i + g^i \qquad (1)$$

where a^i is the specific force (accelerometer output), g^i is the total gravitational acceleration, and $\ddot{r}^i$ is the total acceleration (second derivative of the position vector). The i-frame is an inertial frame whose origin coincides with the center of mass of the Earth. The desired coordinates are usually given in a local, north-east-down (NED) frame, or **n-frame.**

Let ω^n_{in} be the rotation vector of the n-frame with respect to the i-frame expressed in the coordinate system of the n-frame, and let C^i_n be the transformation matrix from the n-frame to the i- frame. Then, differentiating $r^i = C^i_n r^n$ twice with respect to time and substituting into (1) yields:

$$\ddot{r}^n = -2\,\omega^n_{in}\, x\, \dot{r}^n - \omega^n_{in}\, x\, \omega^n_{in} x\, r^n - \dot{\omega}^n_{in} x r^n + a^n + g^n \qquad (2)$$

where $a^n = C^n_i a^i;\ g^n = C^n_i g^i;\ and\ (C^n_i)^{-1} = (C^n_i)^T = C^i_n;$

and where $\dot{C}^i_n = C^i_n [\omega^n_{in} x] \qquad (3)$

defines the dynamics of the orientation of the n-frame with respect to the i-frame, with $[\omega^n_{in} x]$ denoting the skew-symmetric matrix of rotation rates, having the same effect as the vector product. The differential equations (2) and (3) above together define the dynamics of the body motion. The linear perturbation of these equations provides the relationship among the errors in position, velocity, and orientation of the system and the errors of the sensors. The complete derivations can be found in Britting (1971).

Introducing the velocity in addition to position, the second order differential equation (2) and (3) can be converted to a set of first-order differential equations describing the dynamics of the system with the following form:

$$\delta \dot{x} = F\delta x + Gw$$

where δx is the state vector consisting of orientation, position, velocity errors, gyro bias errors, accelerometer bias errors and scale errors. The vector w represents the white noise affecting the gyro and accelerometer measurements. The matrices F and G represent the dynamics and noise coefficient matrices respectively.

It is assumed that the position of the platform is observed directly with the GPS. The observation model which consists of only the observed GPS positions has the following form:

$$\delta \mathrm{y} = H\delta x + v$$

where y are the observed GPS positions, x is the state vector and v is white noise affecting the GPS observations. The design matrix H has all of its elements zero except that three of its columns corresponding to the position, form together an identity matrix.

APPENDIX C

SUMMARY OF RECOMMENDED HARDWARE AND SOFTWARE

	Airborne	Ground	Man-portable
GPS (1), (2)	2 dual-frequency	2 dual-frequency	1 dual-frequency 1 hand-held
GPS antenna (1), (2)	1 ground plane or choke ring 1 airplane	2 ground plane or choke ring	1 ground plane or choke ring (2nd antenna on hand-held receiver)
Radio Modem (3)	1 RDDR-96 (UMF, 450-470 MHz)	1 RDDR-96 (UMF, 450-470 MHz)	1 RDDR-96 (UMF, 450-470 MHz)
INS (4)	LN-210 (including LN-200)	LN-100	LN-200
Moving Map Display (5)	Geographic View/Tracker	Geographic View/Tracker	Geographic View/Tracker

Manufacturers:

(1) Allen Osborne & Associates (805) 495-8420

(2) Trimble Navigation (800) TRI-MBLE

(3) Pacific Crest Instruments (800) 795-1001

(4) Litton Guidance and Control Systems (818) 715-2161

(5) Blue Marble Geographics (207) 582-6747

APPENDIX D

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